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Interaction Effects of a Lower Heated Tube on Pool Boiling of R-124 from an Upper Horizontal Tube

by

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For both tube arrays, the enhancing effect of bubbles from a lower tube was dramatic. This enhancement increased as lower be heat flux increased. However, when upper tube heat fluxes were greater than 20 kW/m^2, all enhancement disappeared.

For a smooth tube array in natural convection, the effect of a lower heated tube on the heat transfer from an upper tube was nall. In nucleate boiling, a P/D of 1.8 gave the best upper tube heat transfer performance and a vigorously nucleating lower be eliminated upper tube hysteresis. With the lower tube unheated and an upper tube heat flux of greater than 3 kW/m^2, the rformance using R-124 was generally better than for R-114. With a nucleating lower tube (at 10 kW/m^2), again the rformance of R-124 was better, but only for upper tube heat fluxes of greater than 40 kW/m^2.

For a TURBO-B tube array, a 30 degree offset of the upper tube reduced the upper tube heat transfer performance (compared the in-line configurations). This may indicate bubbles depart TURBO-B tubes differently than smooth tubes.

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ABSTRACT

An investigation of the interaction effects of a lower heated tube on pool boiling of pure R-124 from an upper horizontal tube was conducted at a saturation temperature of 2.2 °C. The test tubes used were: (1) smooth tubes and (2) deformed surface (TURBO-B) enhanced tubes. The effects of tube spacing/configuration and lower tube heat flux on the heat transfer performance of the upper tube were investigated.

For both tube arrays, the enhancing effect of bubbles from a lower tube was dramatic. This enhancement increased as lower tube heat flux increased. However, when upper tube heat fluxes were greater than 20 kW/m^2, all enhancement disappeared.

For a smooth tube array in natural convection, the effect of a lower heated tube on the heat transfer from an upper tube was small. In nucleate boiling, a P/D of 1.8 gave the best upper tube heat transfer performance and a vigorously nucleating lower tube eliminated upper tube hysteresis. With the lower tube unheated and an upper tube heat flux of greater than 3 kW/m^2, the performance using R-124 was generally better than for R-114. With a nucleating lower tube (at 10 kW/m^2), again the performance of R-124 was better, but only for upper tube heat fluxes of greater than 40 kW/m^2.

For a TURBO-B tube array, a 30 degree offset of the upper tube reduced the upper tube heat transfer performance (compared to the in-line configurations). This may indicate bubbles depart TURBO-B tubes differently than smooth tubes.

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TABLE OF CONTENTS

I. INTRODUCTION 1

II. LITERATURE SURVEY 5
  A. POOL BOILING 5
    1. Natural Convection 5
    2. Boiling Incipience 5
    3. Nucleate Boiling 7
  B. SINGLE TUBE HEAT TRANSFER EXPERIMENTS WITH R-124 AT NAVAL POSTGRADUATE SCHOOL 8
  C. SMALL TUBE ARRAY HEAT TRANSFER PERFORMANCE . . . 9
    1. Natural Convection 10
    2. Nucleate Boiling 12

III. EXPERIMENTAL APPARATUS 15
  A. SYSTEM DESCRIPTION 15
  B. BOILING TEST SECTION 17
    1. Evaporator 17
    2. Evaporator Tubes 18
    3. Tube Configurations 22
  C. CONDENSER SECTION 22
  D. REFRIGERANT STORAGE RESERVOIR 26
  E. OIL SUBSECTION 27

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F. COOLING SUBSYSTEM 27
  1. Ethylene-Glycol/Water Coolant Sump 27
  2. Refrigeration Plants 27
  3. Pumps and Control Valve (VC) 28
G. APPARATUS ENCLOSURE 28
H. INSTRUMENTATION 30
  1. Power Measurement System 30
  2. Temperature Measurement 30
I. DATA ACQUISITION AND REDUCTION PROGRAM 33

IV. EXPERIMENTAL PROCEDURE 37
A. EVAPORATOR DISASSEMBLY PROCEDURE 37
B. EVAPORATOR ASSEMBLY PROCEDURE 38
  1. Evaporator Assembly 38
  2. Leak Test 38
  3. Charging System with Refrigerant 39
    a. From Storage Reservoir 39
    b. From Refrigerant Cylinder 40
  4. Degassing Procedure 40
  5. Data Acquisition Channel Check 41
C. STANDARD OPERATING PROCEDURE 41
D. DATA FILES 42

V. DISCUSSION OF RESULTS 50
A. REPRODUCIBILITY/REPEATABILITY 50
B. INFLUENCE OF THE LOWER TUBE 59

1. The Effect of Tube Spacing 62
    a. Smooth Tubes with Lower Tube Unheated . . 62
    b. Smooth Tubes with LTHFS of 1 kW/m^2 65
    c. Smooth Tubes with LTHFS of 5 kW/m^2 68
    d. Smooth Tubes with LTHFS of 10 kW/m^2 . . . 71
    e. Smooth Tubes with LTHFS of 20 kW/m^2 . . . 73
    f. Smooth Tubes with UTHFS equal LTHFS . . . 76
    g. TURBO-B Tubes with Lower Tube Unheated . . 80
    h. TURBO-B Tubes with LTHFS of 1 kW/m^2 . . . 80
    i. TURBO-B Tubes with LTHFS of 5 kW/m^2 . . . 83
    j. TURBO-B Tubes with LTHFS of 10 kW/m^2 . . . 83
    k. TURBO-B Tubes with LTHFS of 20 kW/m^2 . . . 86
    l. TURBO-B Tubes with UTHFS equal LTHFS . . . 86
2. The Effect of a Fixed Lower Tube Heat Flux . . 86
    a. Smooth Tubes with P/D of 2.0 86
    b. Smooth Tubes with P/D of 1.8 92
    c. Smooth Tubes with P/D of 1.5 94
    d. Smooth Tubes with P/D of 1.2 97
    e. Smooth Tubes with P/D of 1.2 (Rotated 30°) 97
    f. TURBO-B Tubes with P/D of 2.0 102
    g. TURBO-B Tubes with P/D of 1.8 102
    h. TURBO-B Tubes with P/D of 1.5 106
    i. TURBO-B Tubes with P/D of 1.2 106
    j. TURBO-B Tubes with P/D of 1.2 (Rotated 30°) 109

3. The Effect of a Variable Lower Tube Heat Flux 109
a. Smooth Tubes with P/D of 2.0 109
b. Smooth Tubes with P/D of 1.8 112
c. Smooth Tubes with P/D of 1.5 115
d. Smooth Tubes with P/D of 1.2 115
e. Smooth Tubes with P/D of 1.2 (Rotated 30°) 115
f. TURBO-B Tubes with P/D of 2.0 118
g. TURBO-B Tubes with P/D of 1.8 120
h. TURBO-B Tubes with P/D of 1.5 120
i. TURBO-B Tubes with P/D of 1.2 120
j. TURBO-B Tubes with P/D of 1.2 (Rotated 30°) 124
C. R-124/R-114 PERFORMANCE COMPARISON 124

VI. CONCLUSIONS 129

VII. RECOMMENDATIONS 130

APPENDIX A. PROGRAM SETUPJY 131

APPENDIX B. PROGRAM DRPJY 134

APPENDIX C. REPRESENTATIVE DATA SET 147

APPENDIX D. SAMPLE CALCULATIONS 155
- A. SMOOTH TEST TUBE DIMENSIONS 155
- B. MEASURED PARAMETERS 155
- C. OUTER WALL TEMPERATURE OF THE UPPER TEST TUBE . 156
  - 1. Surface Area of Smooth Tube 156
  - 2. Heater Power 156
  - 3. Average Inside Tube Temperature 156
  - 4. Outside Wall Tube Temperature 156
  - 5. Tube Wall Superheat 156
- D. R-124 PROPERTIES AT FILM TEMPERATURE 157
  - 1. Film Temperature 157
  - 2. Dynamic Viscosity 157
  - 3. Density 157
  - 4. Kinematic Viscosity 157
  - 5. Thermal Conductivity 157
  - 6. Specific Heat 158
  - 7. Thermal Diffusivity 158
  - 8. Volumetric Thermal Expansion Coefficient . . 158
  - 9. Prandtl Number 158
- E. HEAT FLUX THROUGH NON-BOILING TUBE LENGTHS . . 158
- F. HEAT FLUX THROUGH BOILING TUBE LENGTH 159

APPENDIX E. UNCERTAINTY ANALYSIS 160
- A. HEAT TRANSFER RATE UNCERTAINTY 161
- B. SURFACE AREA UNCERTAINTY 161
- C. WALL SUPERHEAT UNCERTAINTY 162

D. HEAT FLUX UNCERTAINTY 163
E. HEAT TRANSFER COEFFICIENT UNCERTAINTY 164

LIST OF REFERENCES 166

INITIAL DISTRIBUTION LIST 169

LIST OF TABLES

TABLE 1. R-114/R-124 PHYSICAL PROPERTIES AT 2.2 °C . . 2
TABLE 2. DIMENSIONS OF TEST TUBES 18
TABLE 3. HP-3497A CHANNEL ASSIGNMENTS 36
TABLE 4. LIST OF DATA RUNS 44
TABLE 5. RESULTS OF UNCERTAINTY ANALYSIS 165

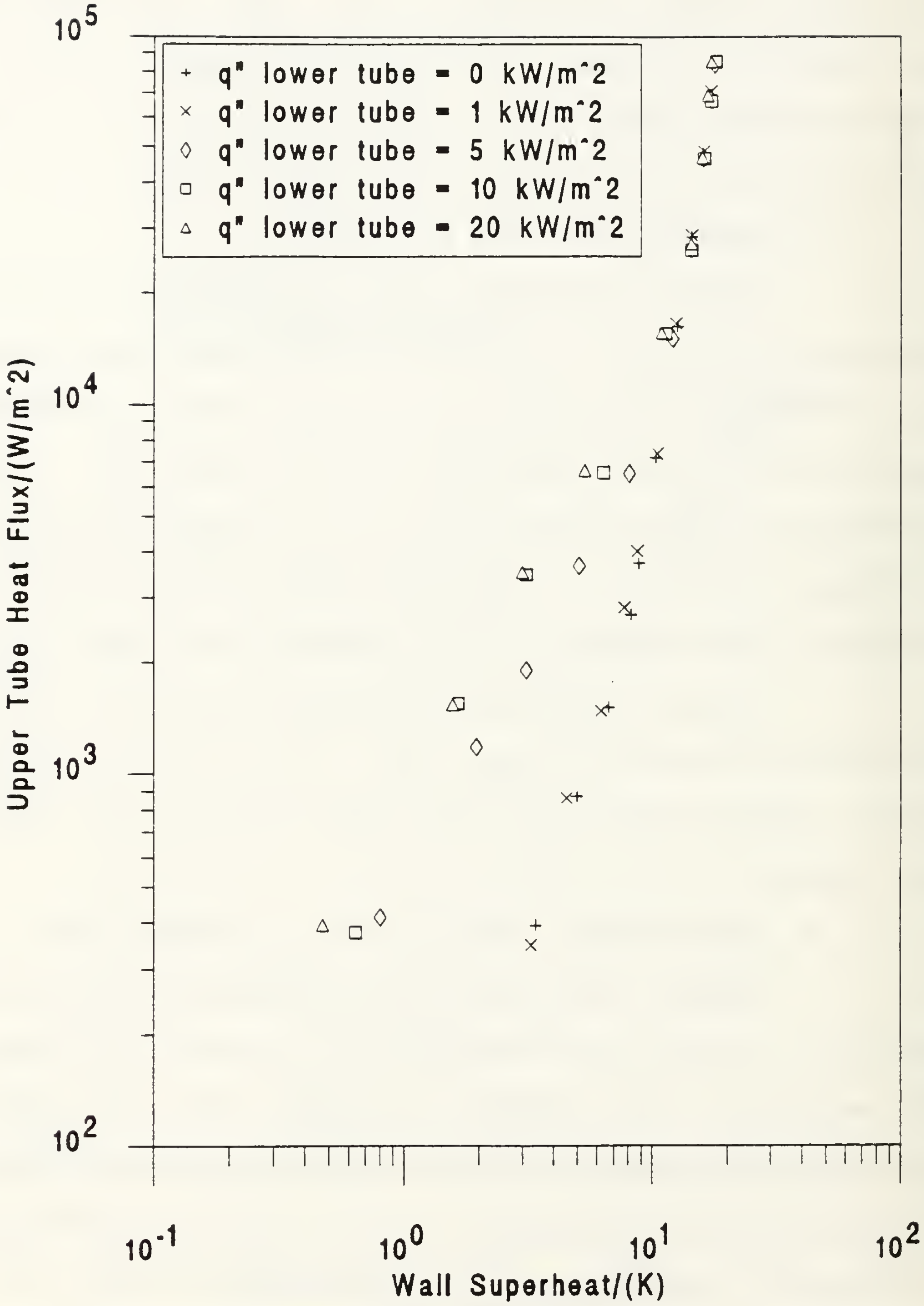

Figure 5.30 Comparison of Lower Tube Heat Flux Settings on Decreasing Heat Flux of Smooth Tubes with P/D of 1.5

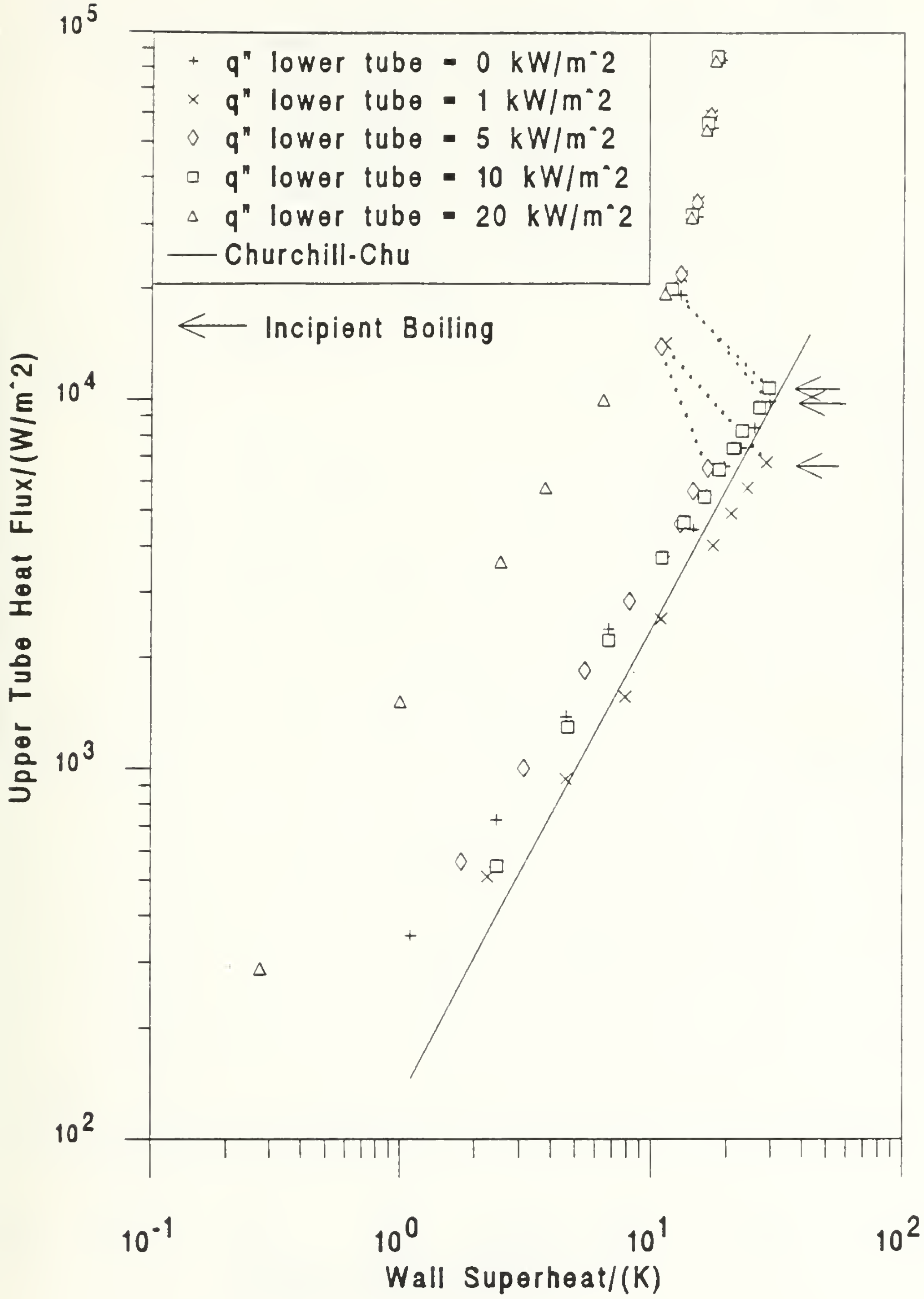

Figure 5.31 Comparison of Lower Tube Heat Flux Settings on Increasing Heat Flux of Smooth Tubes with P/D of 1.2

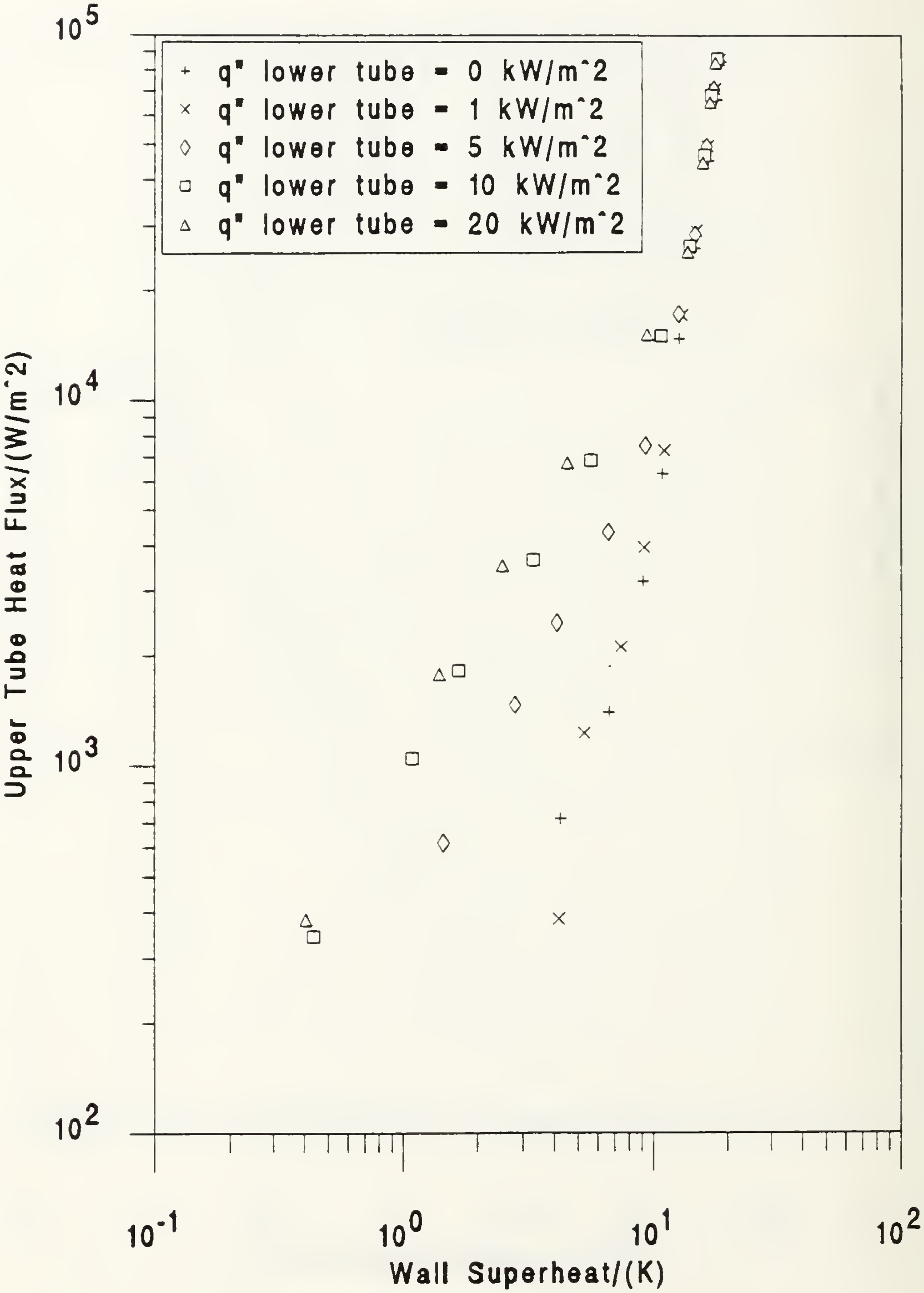

Figure 5.32 Comparison of Lower Tube Heat Flux Settings on Decreasing Heat Flux of Smooth Tubes with P/D of 1.2

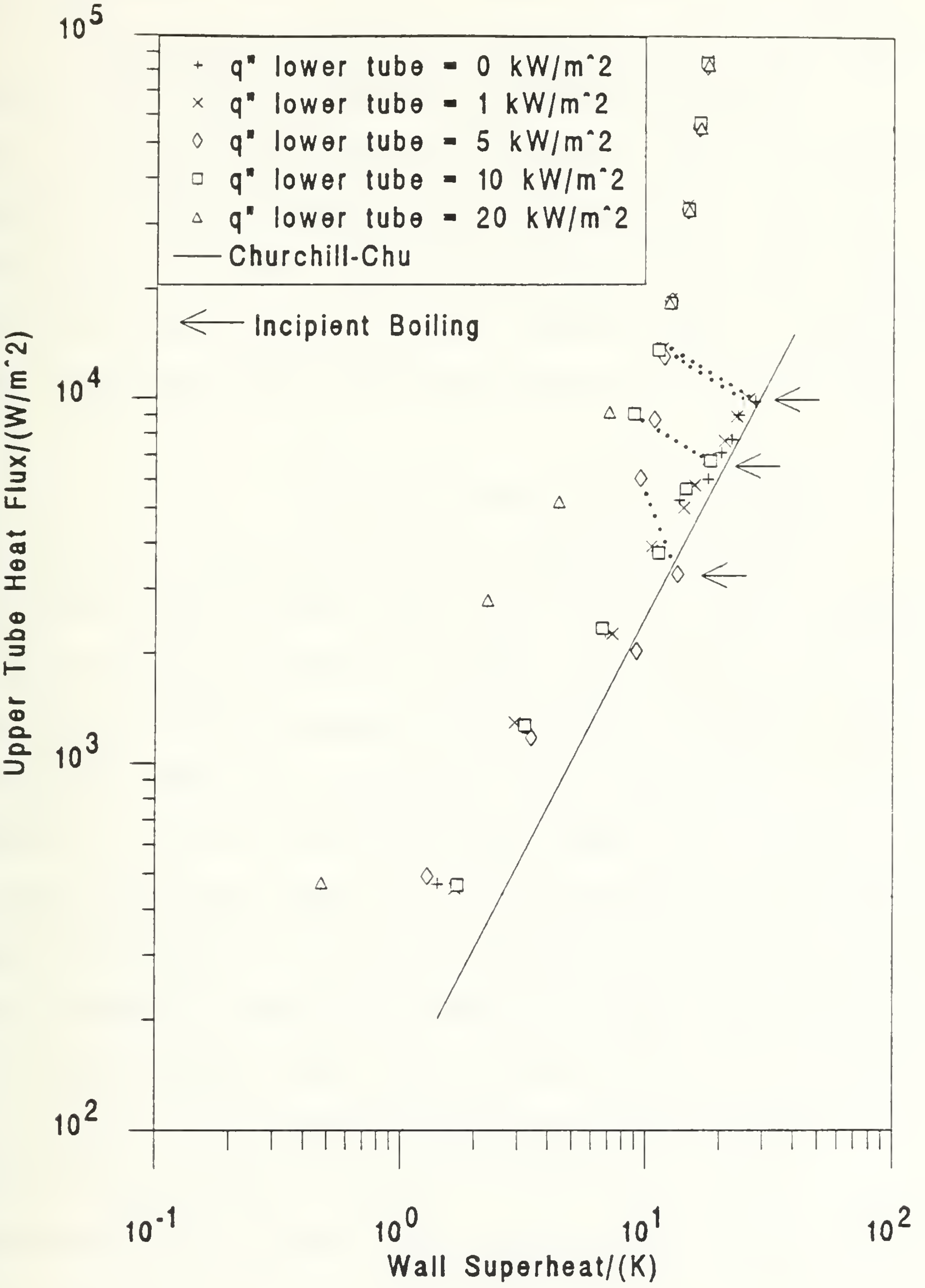

Figure 5.33 Comparison of Lower Tube Heat Flux Settings on Increasing Heat Flux of Smooth Tubes with P/D of 1.2 (Rotated 30°)

previously. This might be due to the offset orientation of the upper tube causing the data to be less scattered.

Figure 5.34 shows the decreasing heat flux data for the data runs shown in Figure 5.33. At high heat fluxes, all the data lay on one nucleate boiling curve. Below 10 kW/m^2, separate curves are formed and as seen before. Significant enhancement of heat transfer from an upper tube is obtained when the lower tube is nucleating with a heat flux larger than 5 kW/m^2.

f. TURBO-B Tubes with P/D of 2.0

Figure 5.35 shows the decreasing heat flux data for the TURBO-B tubes taken at five lower tube heat flux settings. At the start of each run, a very consistent boiling curve is seen above 20 kW/m^2, indicating that above a UTHFS of 20 kW/m^2, there is no enhancement from increasing the LTHFS. Below 10 kW/m^2, raising the LTHFS does increase the heat transfer performance of the upper tube. At an upper tube heat flux of 2 kW/m^2, an increase in performance of 2.4 is found going from an unheated lower tube to a LTHFS of 20 kW/m^2, compared to an increase of 3.6 for the smooth tube array (Figure 5.26).

g. TURBO-B Tubes with P/D of 1.8

Figure 5.36 shows the decreasing heat flux data for the TURBO-B tubes taken at five lower tube heat flux settings. Similar results are found compared to the P/D of 2.0 case. At

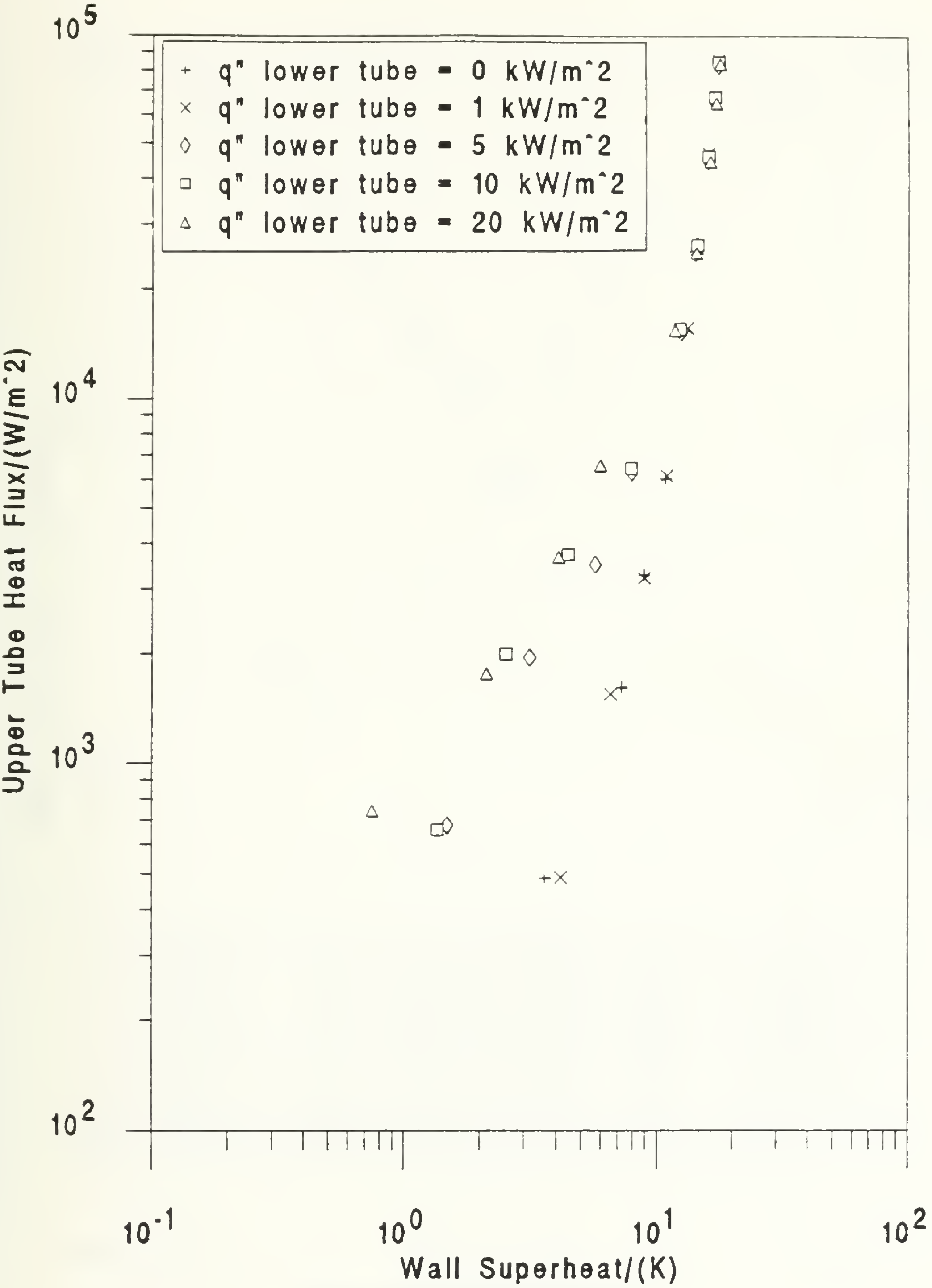

Figure 5.34 Comparison of Lower Tube Heat Flux Settings on Decreasing Heat Flux of Smooth Tubes with P/D of 1.2 (Rotated 30°)

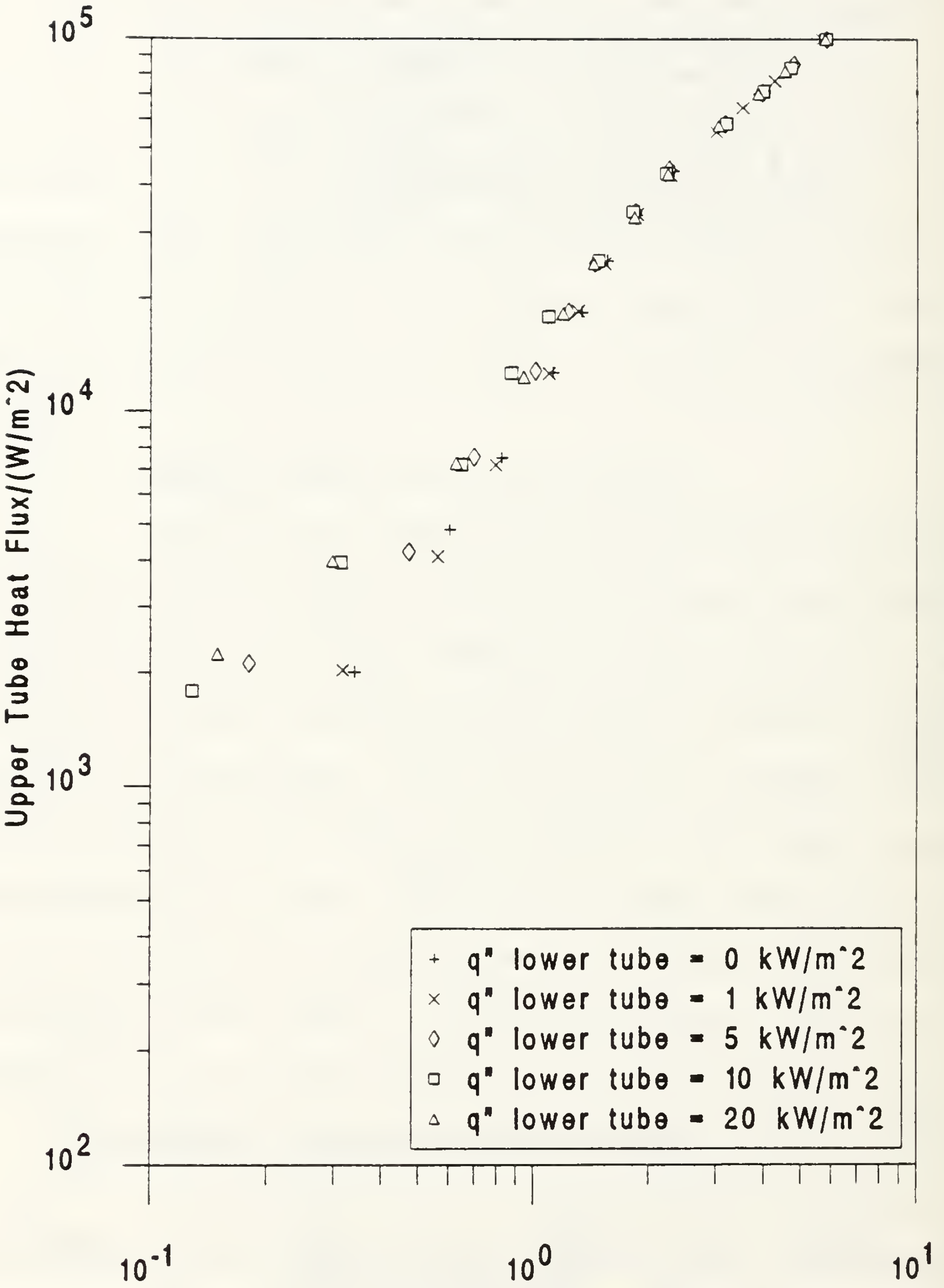

Figure 5.35 Comparison of Lower Tube Heat Flux Settings on Decreasing Heat Flux of TURBO-B Tubes with P/D of 2.0

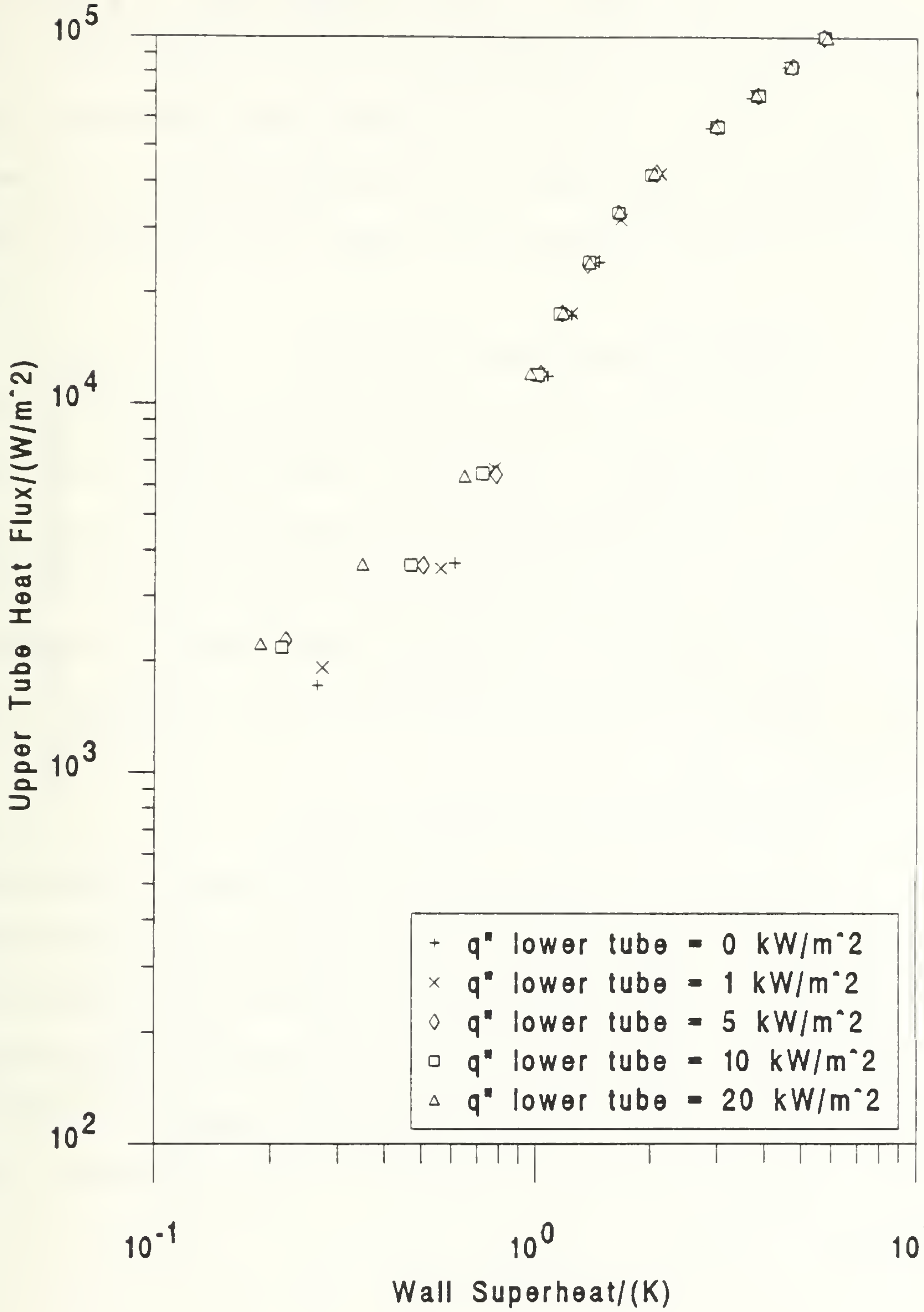

Figure 5.36 Comparison of Lower Tube Heat Flux Settings on Decreasing Heat Flux of TURBO-B Tubes with P/D of 1.8

an upper tube heat flux of 2 kW/m^2, an increase in performance of 1.6 is found going from a unheated lower tube to a LTHFS of 20 kW/m^2, compared to an increase of 3.7 for the smooth tube array (Figure 5.28). Unlike the smooth tube case where a P/D of 1.8 produced the best heat transfer performance in nucleate boiling, no optimal P/D ratio was found for the TURBO-B tube array.

h. TURBO-B Tubes with P/D of 1.5

Figure 5.37 shows the decreasing heat flux data for the TURBO-B tubes taken at five lower tube heat flux settings. Similar results are found compared to the P/D of 1.8 case. At an upper tube heat flux of 2 kW/m^2, an increase in performance of 2.2 is found going from a unheated lower tube to a LTHFS of 20 kW/m^2, compared to an increase of 3.5 for the smooth tube array (Figure 5.30).

i. TURBO-B Tubes with P/D of 1.2

Figure 5.38 shows the decreasing heat flux data for the TURBO-B tubes taken at five lower tube heat flux settings. Similar results are found compared to the P/D of 1.5 case. At an upper tube heat flux of 2 kW/m^2, an increase in performance of 2.2 is found going from a unheated lower tube to a LTHFS of 20 kW/m^2, compared to an increase of 5.4 for the smooth tube array (Figure 5.32).

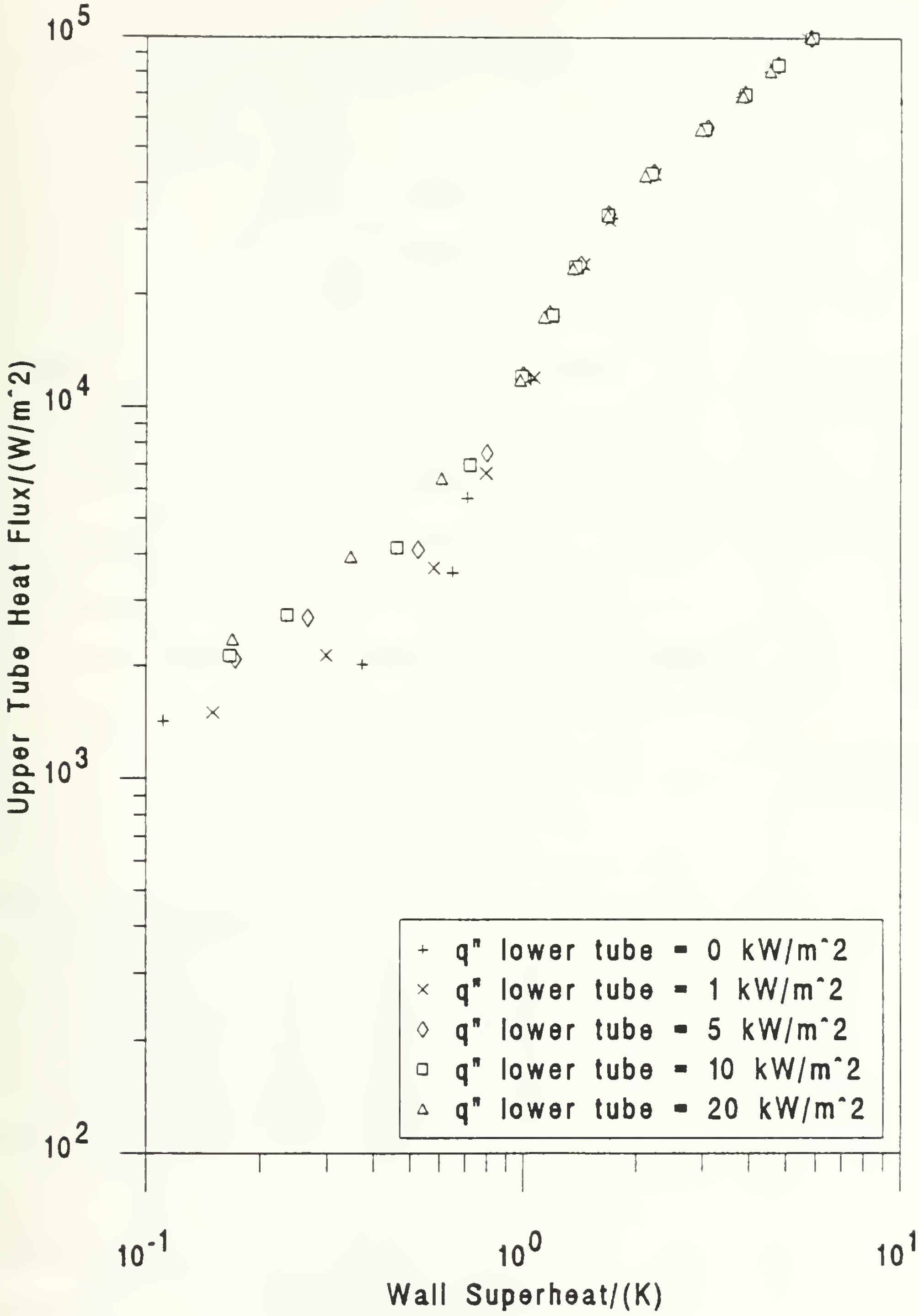

Figure 5.37 Comparison of Lower Tube Heat Flux Settings on Decreasing Heat Flux of TURBO-B Tubes with P/D of 1.5

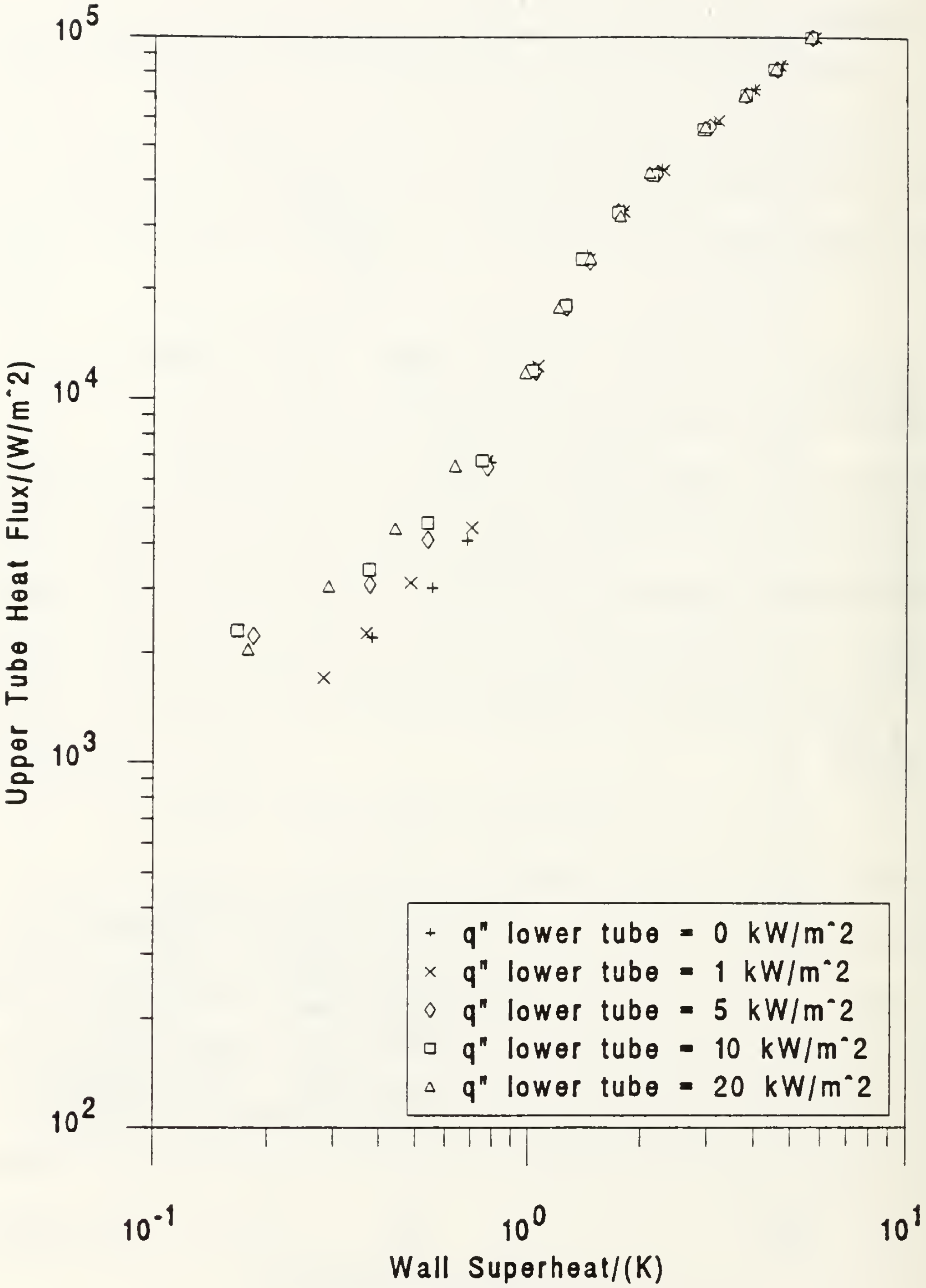

Figure 5.38 Comparison of Lower Tube Heat Flux Settings on Decreasing Heat Flux of TURBO-B Tubes with P/D of 1.2

j. TURBO-B Tubes with P/D of 1.2 (Rotated 30°)

Figure 5.39 shows the decreasing heat flux data for the TURBO-B tubes taken at five lower tube heat flux settings. A very consistent boiling curve is again seen above 10 kW/m^2. Below 10 kW/m^2, the data seems less scattered and slightly to the left of any other configuration, indicating that rotating the upper tube reduces the enhancement produced from increasing the LTHFS in the low heat flux regions. At an upper tube heat flux of 2 kW/m^2, an increase in performance of 1.7 is found going from a unheated lower tube to a LTHFS of 20 kW/m^2, compared to an increase of 3.5 for the smooth tube array (Figure 5.34).

3. The Effect of a Variable Lower Tube Heat Flux

a. Smooth Tubes with P/D of 2.0

Figure 5.40 shows the heat transfer performance of an upper tube, held at a constant heat flux, as the lower tube heat flux is varied. The three fixed UTHFS used were 5, 10 and 20 kW/m^2. The labeling in the plot legend describes which data were taken using increasing or decreasing lower tube heat flux. The sharp transitions in the increasing curves are the points where the lower tube nucleated and caused the upper tube to shift from natural convection to nucleate boiling (visually verified during the data run), significantly increasing the upper tube heat transfer coefficient, as expected. The maximum upper tube heat transfer coefficient

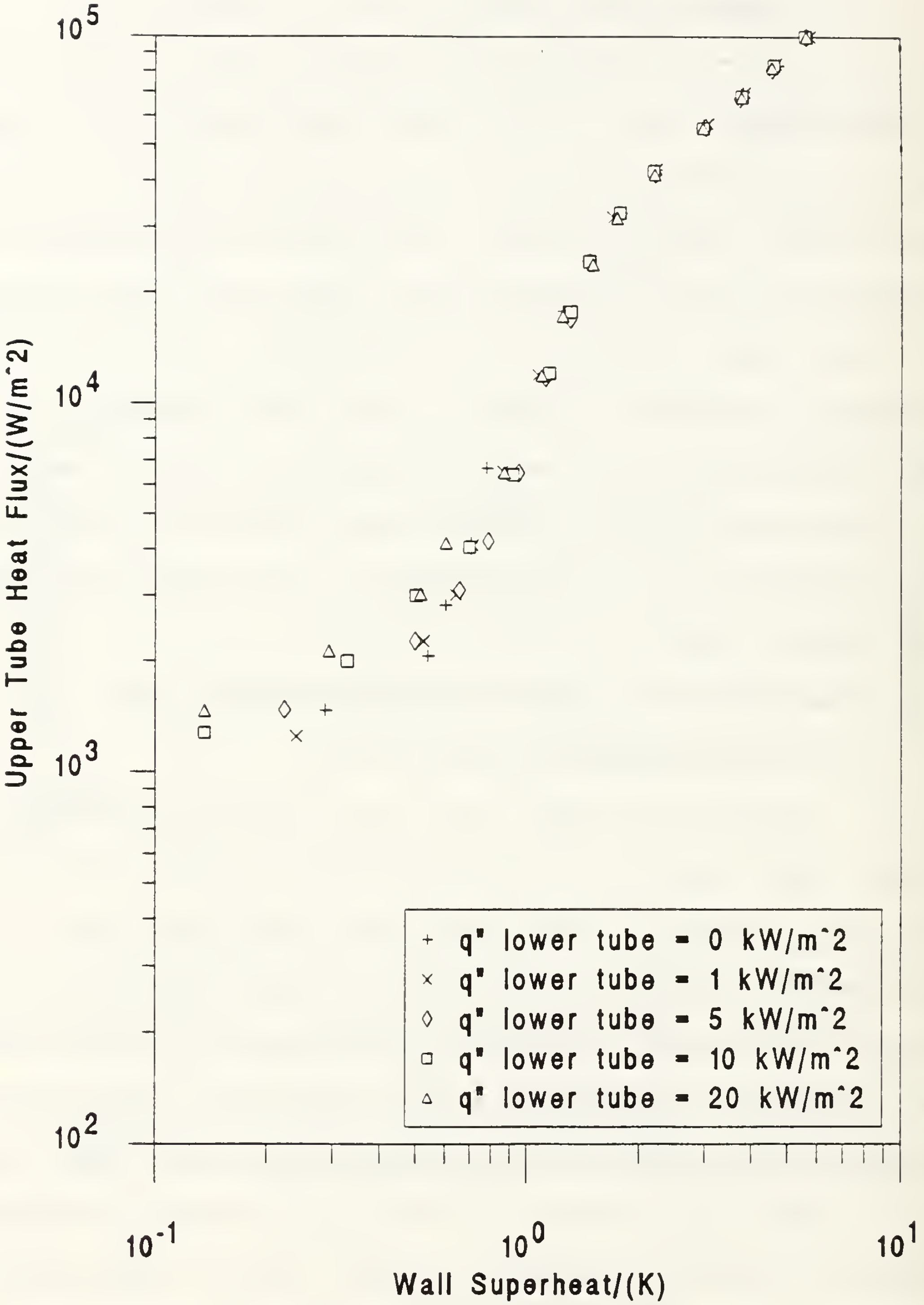

Figure 5.39 Comparison of Lower Tube Heat Flux Setting on Decreasing Heat Flux of TURBO-B Tubes with P/D of 1.2 (Rotated 30°)

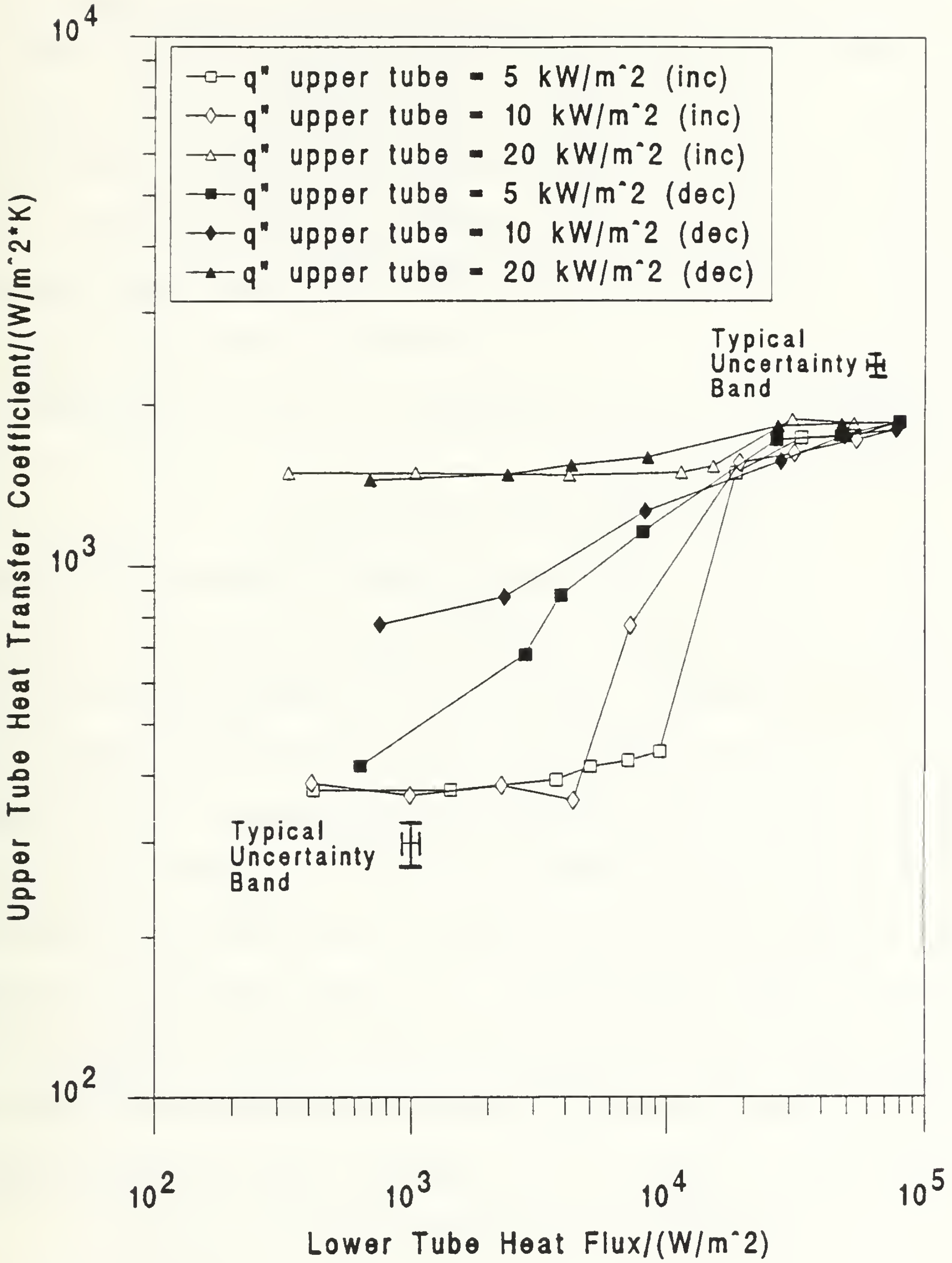

Figure 5.40 Heat Transfer Performance of a Smooth Upper Tube at a Constant Heat Flux for a P/D of 2.0

for all three UTHFS was 1850 W/m^2·K, which indicates that at a lower tube heat flux of 80 kW/m^2, the heat transfer performance of the upper tube is independent of the lower tube heat flux. The decreasing curves show that for an UTHFS of 20 kW/m^2, the lower tube heat flux has little influence on the upper tube heat transfer. For the UTHFS of 10 kW/m^2, as the lower tube heat flux is decreased, the upper tube remains in nucleate boiling, but for the UTHFS of 5 kW/m^2, the upper tube returns to the natural convection region as the lower tube heat flux is decreased.

b. Smooth Tubes with P/D of 1.8

Figure 5.41 shows the heat transfer performance of an upper tube, held at a constant heat flux, as the lower tube heat flux is varied. Similar results were obtained as in the P/D of 2.0 case, except that the curves did not merge at the highest heat flux setting. The maximum heat transfer coefficient for the UTHFS of 5 and 10 kW/m^2 converged at approximately 1700 W/m^2·K and for the UTHFS of 20 kW/m^2 the value was about 1900 W/m^2·K. It is not known why the curves did not merge at high lower tube heat fluxed. Comparing these results to the P/D of 2.0 results, at the smallest lower tube heat fluxes, the P/D of 1.8 provides better heat transfer.

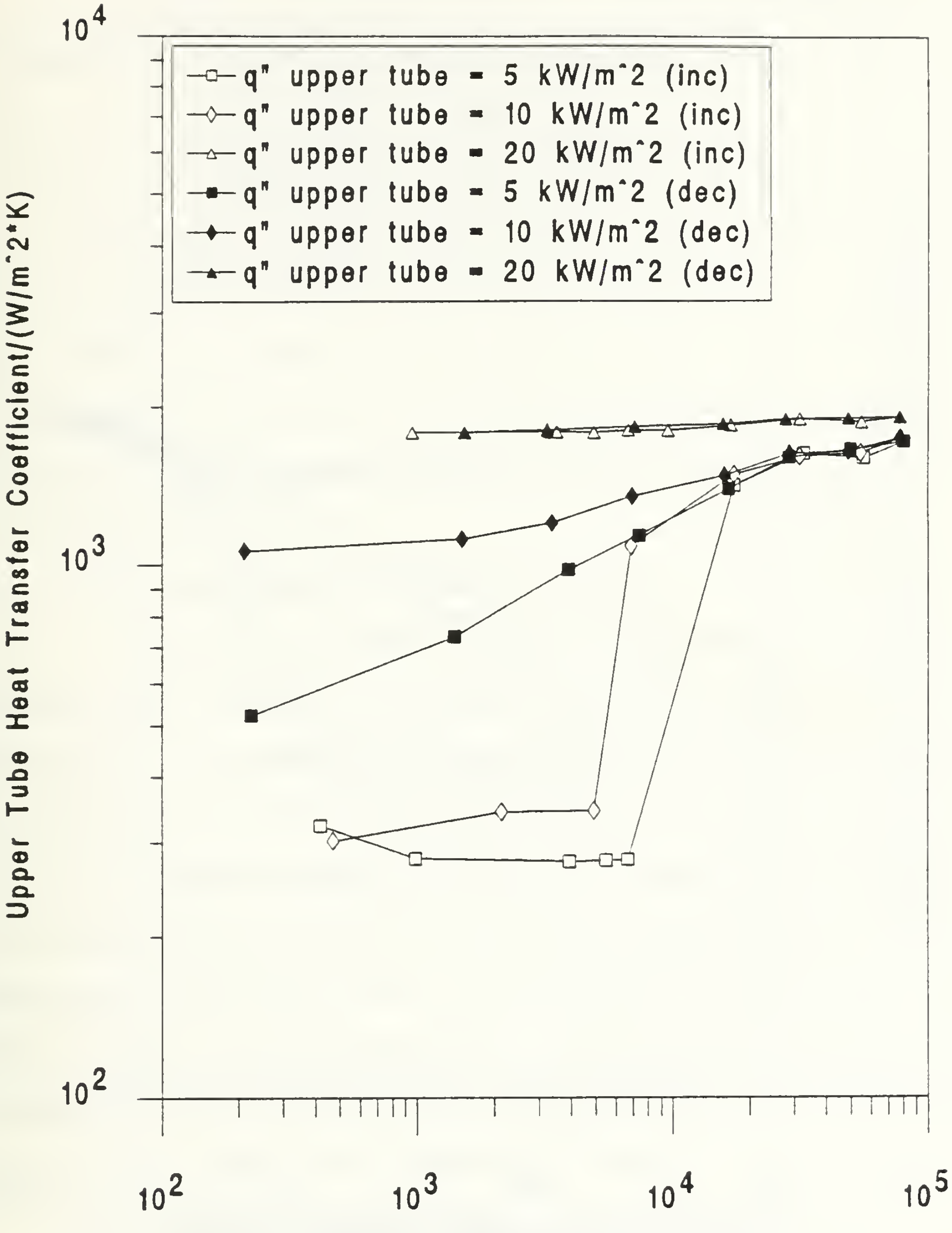

Figure 5.41 Heat Transfer Performance of a Smooth Upper Tube at a Constant Heat Flux for a P/D of 1.8

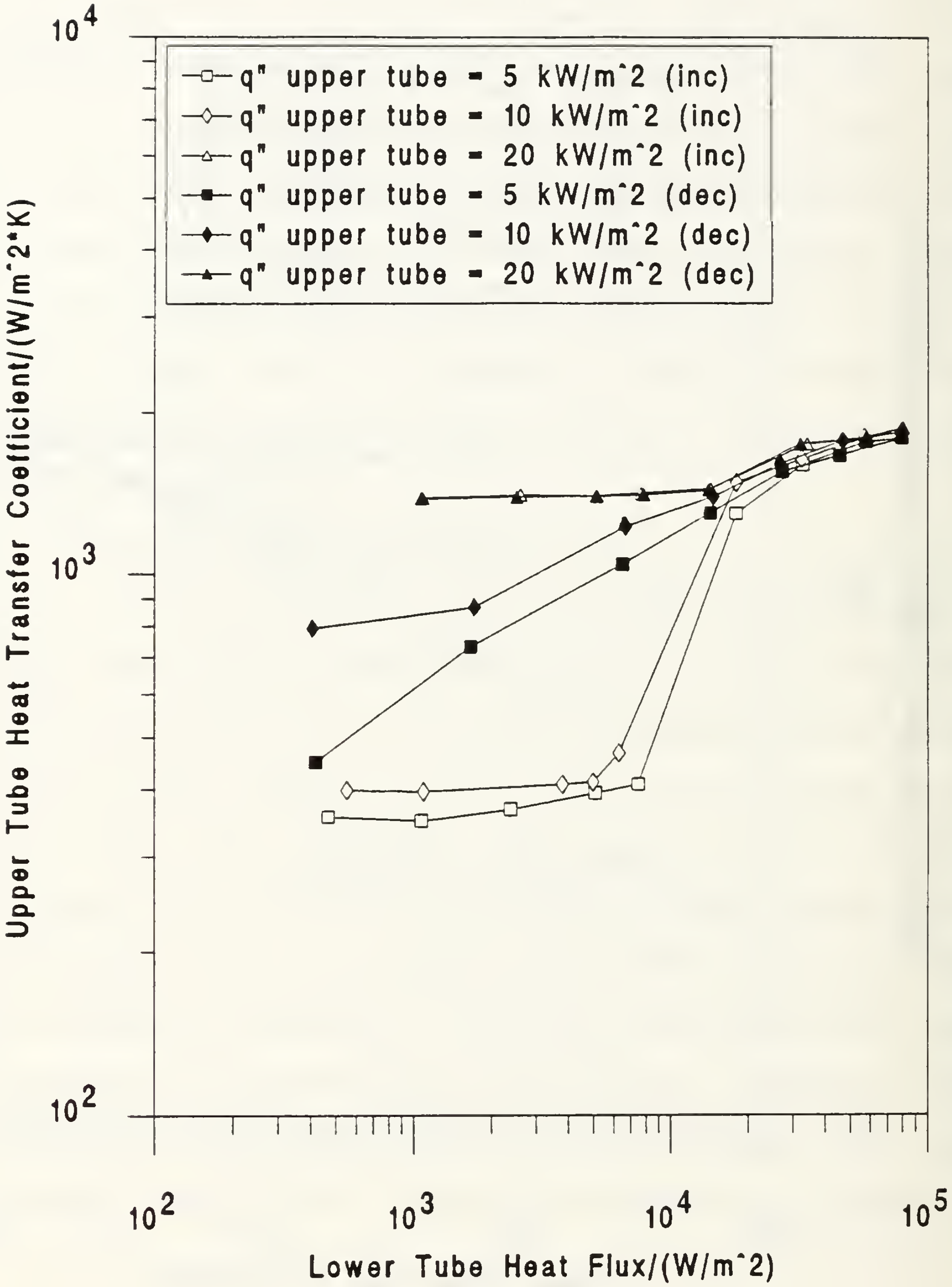

Figure 5.42 Heat Transfer Performance of a Smooth Upper Tube at a Constant Heat Flux for a P/D of 1.5

c. Smooth Tubes with P/D of 1.5

Figure 5.42 shows the heat transfer performance of an upper tube, held at a constant heat flux, as the lower tube heat flux is varied. The maximum heat transfer coefficient for all three of the UTHFS converged at approximately 1800 $W/m^2 \cdot K$, similar to the P/D of 2.0 case. The decreasing curves show very similar behavior found at a P/D of 2.0. Comparing these results to data of a P/D of 2.0 and 1.8, a P/D of 2.0 and 1.5 are similar in the amount of enhancement achieved, whereas a P/D of 1.8 outperforms them both, in the mid to low heat flux regions.

d. Smooth Tubes with P/D of 1.2

Figure 5.43 shows the heat transfer performance of an upper tube, held at a constant heat flux, as the lower tube heat flux is increased. The maximum heat transfer coefficient for all three of the UTHFS converged, as did the P/D of 2.0 and 1.5, at approximately 1990 $W/m^2 \cdot K$, highest value of all the configurations tested. Therefore, the best heat transfer performance was given by a P/D ratio of 1.8 when the lower tube heat flux was held constant, but a P/D ratio of 1.2 when the upper tube heat flux was held constant. No decreasing curves were recorded for these data runs.

e. Smooth Tubes with P/D of 1.2 (Rotated 30°)

Figure 5.44 shows the heat transfer performance of an upper tube, held at a constant heat flux, as the lower tube

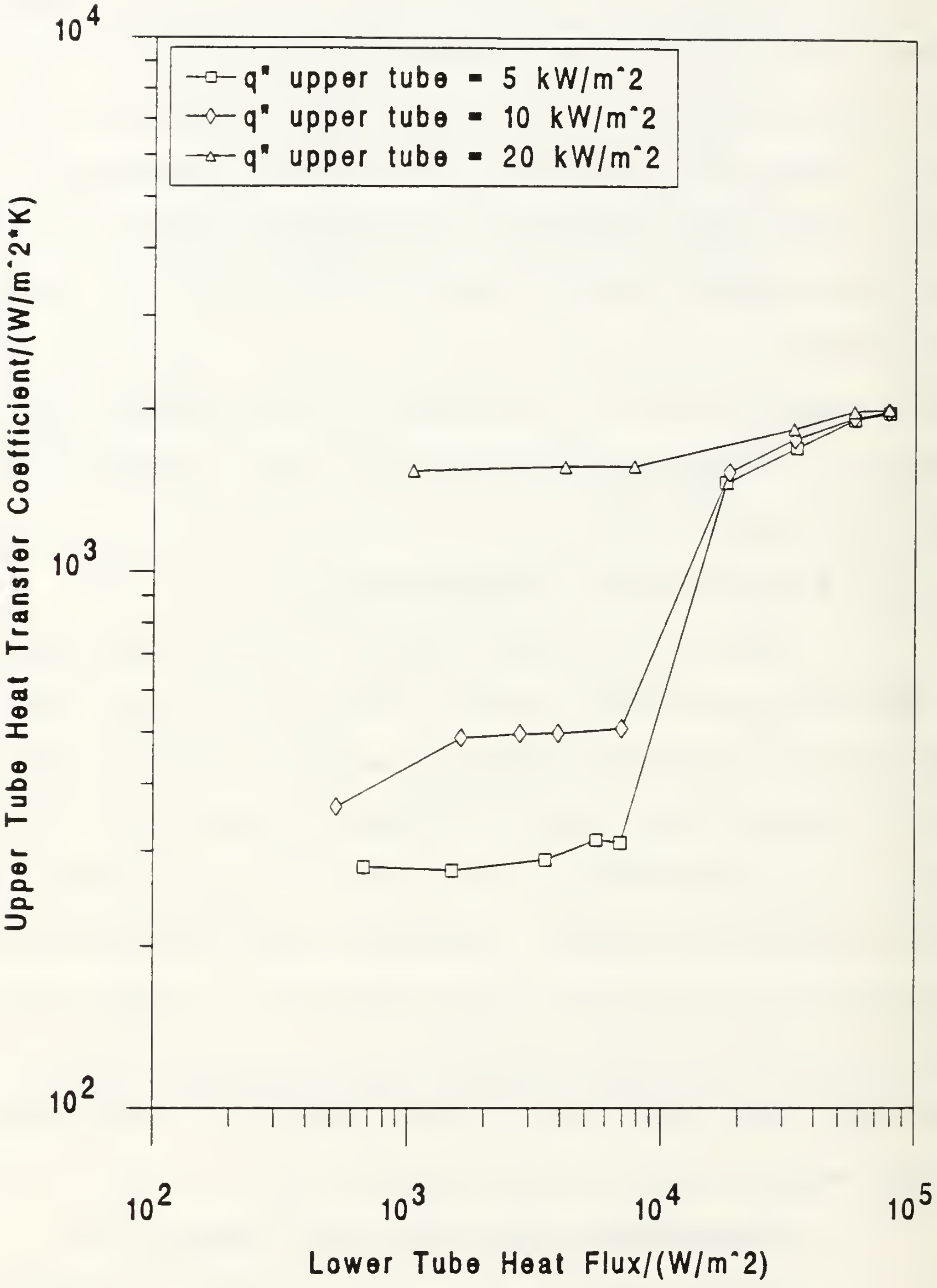

Figure 5.43 Heat Transfer Performance of a Smooth Upper Tube at a Constant Heat Flux for a P/D of 1.2

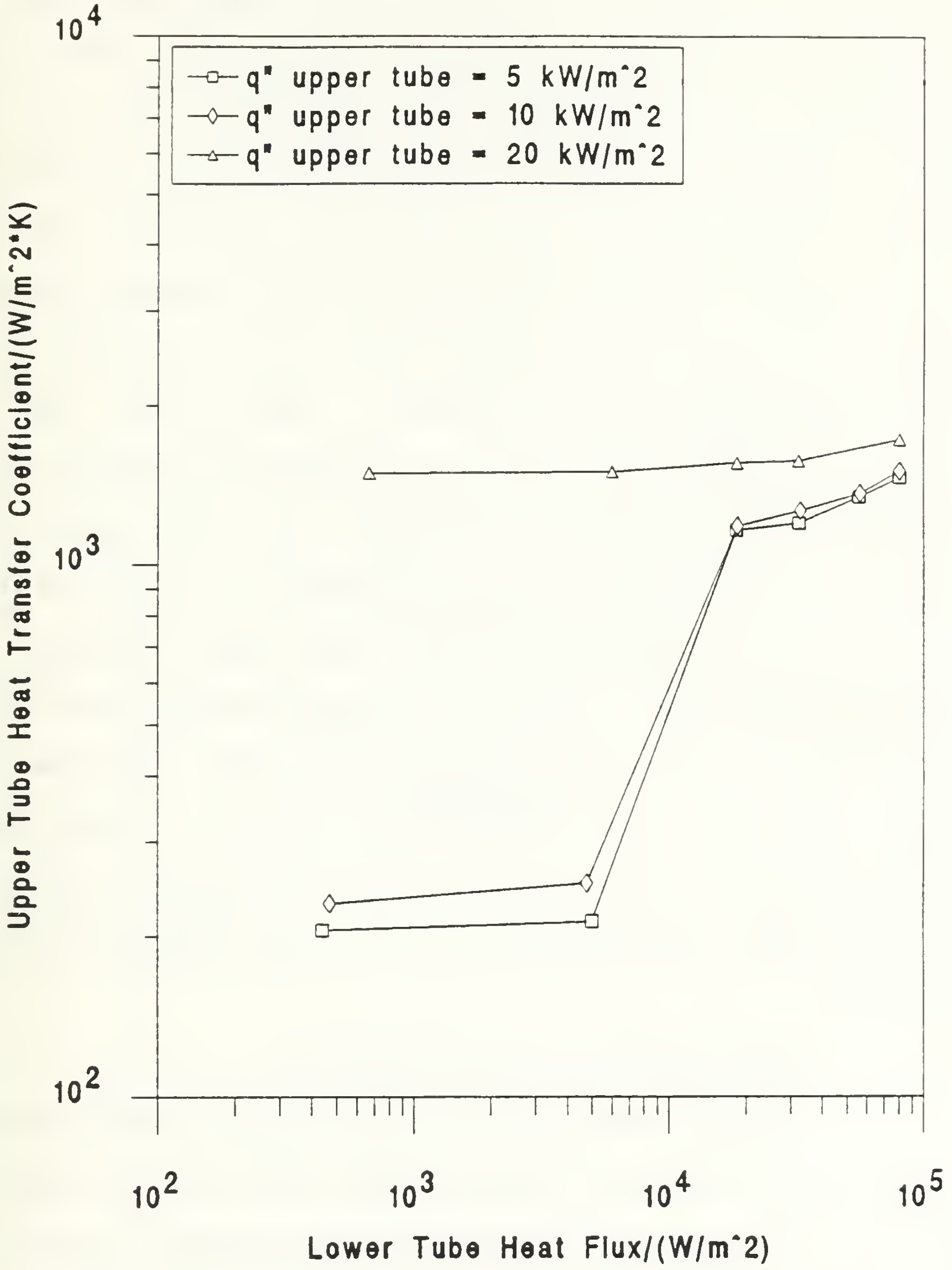

Figure 5.44 Heat Transfer Performance of a Smooth Upper Tube at a Constant Heat Flux for a P/D of 1.2 (Rotated 30°)

heat flux is increased. As seen for the P/D of 1.8 case, the curves do not merge at the highest lower tube heat flux. The maximum heat transfer coefficient for the two lower curves converged at about 1500 $W/m^2 \cdot K$ and the upper curve was 1725 $W/m^2 \cdot K$. Comparing Figures 5.43 and 5.44, for an UTHFS of 20 kW/m^2, the data curves are identical for lower tube heat fluxes up to 8 kW/m^2, indicating that the forced convection effects from the lower tube have very little influence on the upper tube heat transfer behavior. Above lower tube heat fluxes of 10 kW/m^2, the in-line configuration provides better heat transfer performance because the lower tube is in nucleate boiling and all of the bubbles are impacting the upper tube providing enhancement by *bubble pumping;* as opposed to the offset configuration, where most of the bubbles coming off the lower tube miss the upper tube. The same idea holds true for the other data curves. The in-line configurations are more enhanced due to *bubble pumping* from the lower tube. No decreasing curves were recorded for these data runs.

f. TURBO-B Tubes with P/D of 2.0

Figure 5.45 shows the heat transfer performance of an upper tube, held at a constant heat flux, as the lower tube heat flux is decreased. At high lower tube heat fluxes, all three of the UTHFS appear to perform almost equally. For an UTHFS of 20 kW/m^2, the lower tube heat flux has little

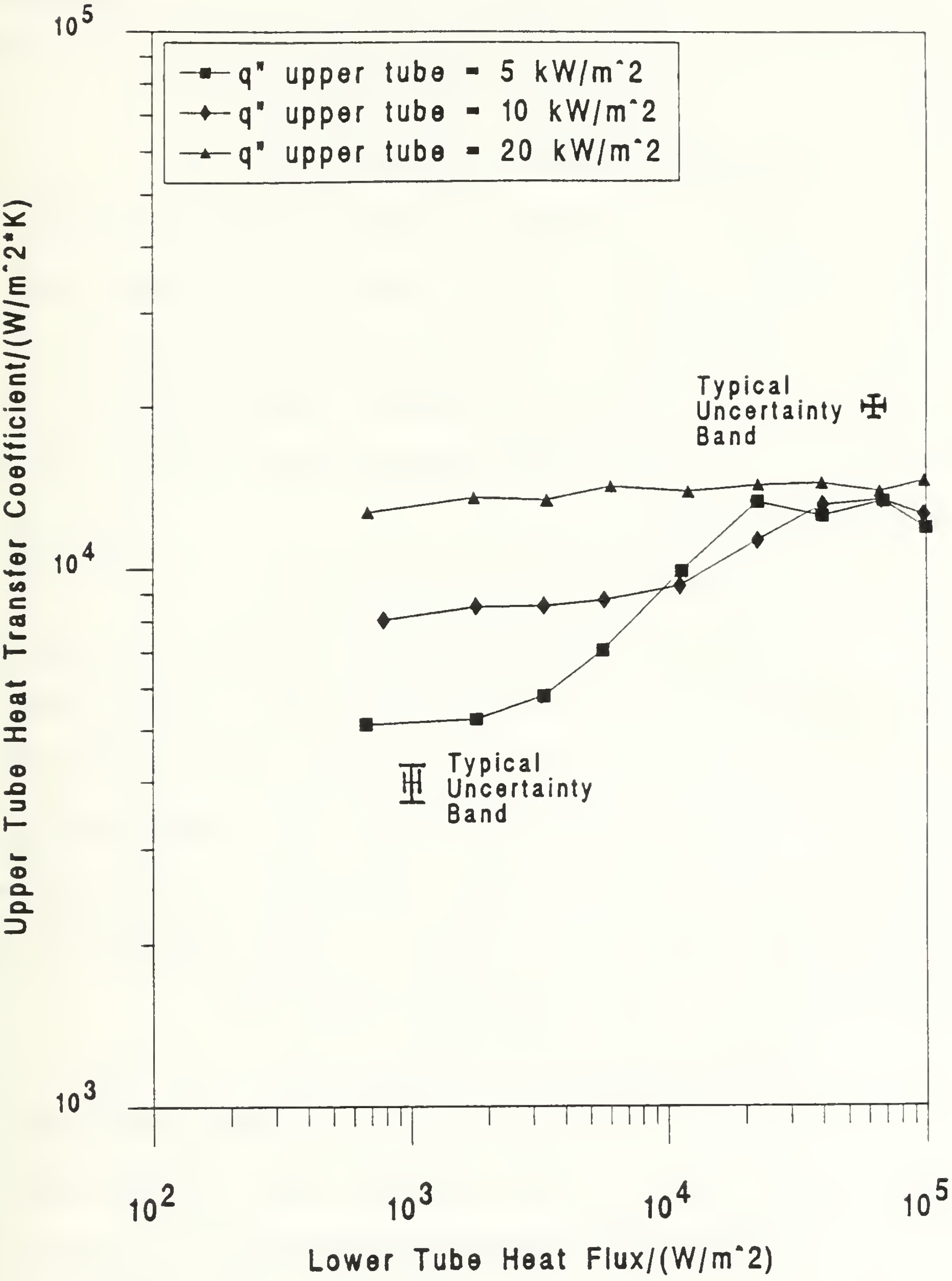

Figure 5.45 Heat Transfer Performance of a TURBO-B Upper Tube at a Constant Heat Flux for a P/D of 2.0

influence on the upper tube heat transfer and for an UTHFS of 5 and 10 kW/m^2, as the lower tube heat flux is decreased so follows the performance of the upper tube (more for 5 than 10 kW/m^2).

g. TURBO-B Tubes with P/D of 1.8

Figure 5.46 shows the heat transfer performance of an upper tube, held at a constant heat flux, as the lower tube heat flux is decreased. Comparing these curves to the ones for a P/D of 2.0, a small enhancement in performance is gained in the mid and low heat flux regions using a P/D of 1.8, which is an expected result.

h. TURBO-B Tubes with P/D of 1.5

Figure 5.47 shows the heat transfer performance of an upper tube, held at a constant heat flux, as the lower tube heat flux is decreased. There is very little difference in performance between a P/D of 1.5 and 1.8. Comparing the P/D of 1.5 to the 2.0 data, a small decrease in performance is noted for lower tube heat fluxes > 20 kW/m^2 using the P/D of 1.5 configuration, which cannot be explained.

i. TURBO-B Tubes with P/D of 1.2

Figure 5.48 shows the heat transfer performance of an upper tube, held at a constant heat flux, as the lower tube heat flux is decreased. Similar performance is noted for a P/D ratio of 1.2 and 1.5, therefore, the comments made previously still apply.

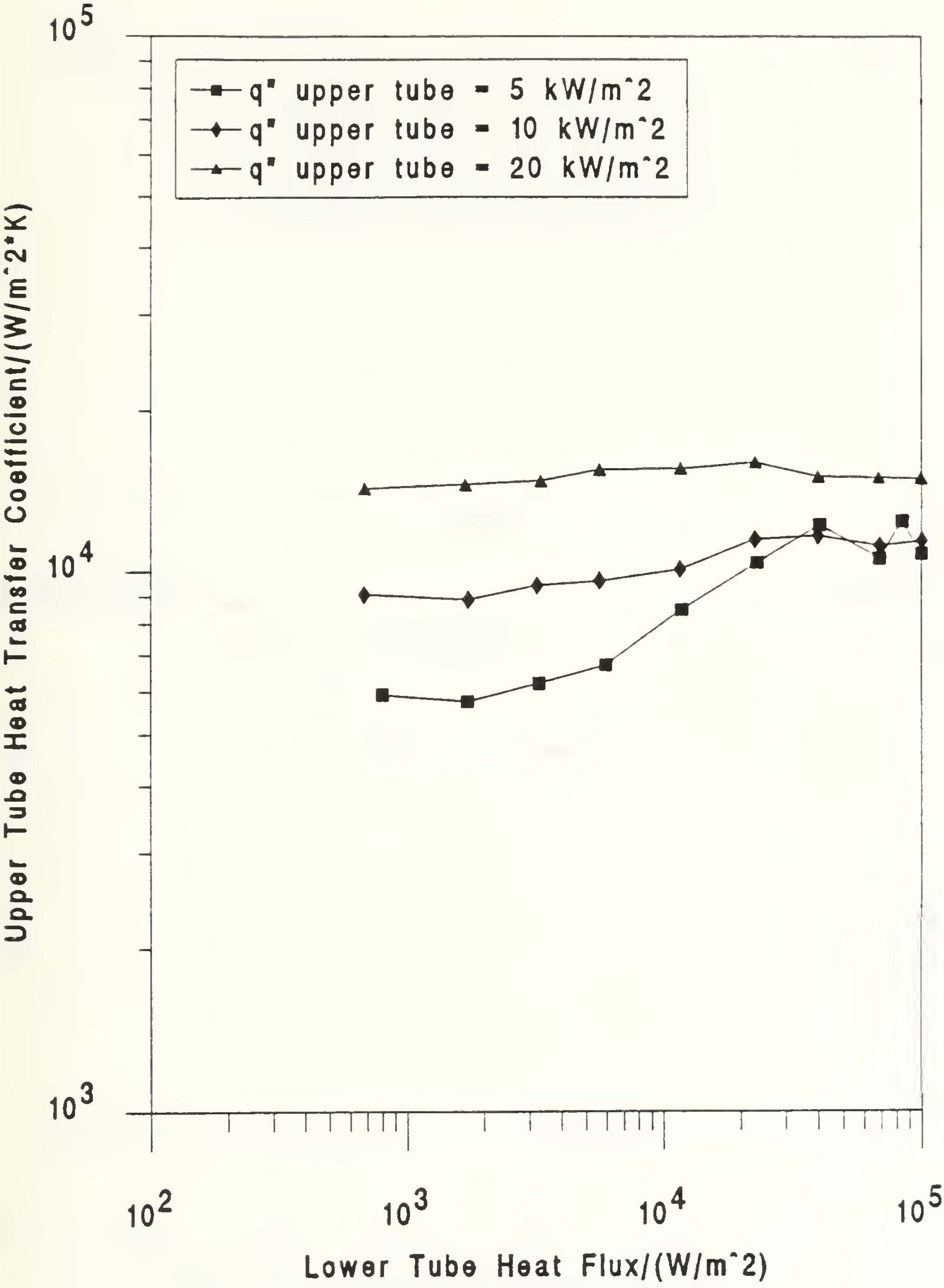

Figure 5.46 Heat Transfer Performance of a TURBO-B Upper Tube at a Constant Heat Flux for a P/D of 1.8

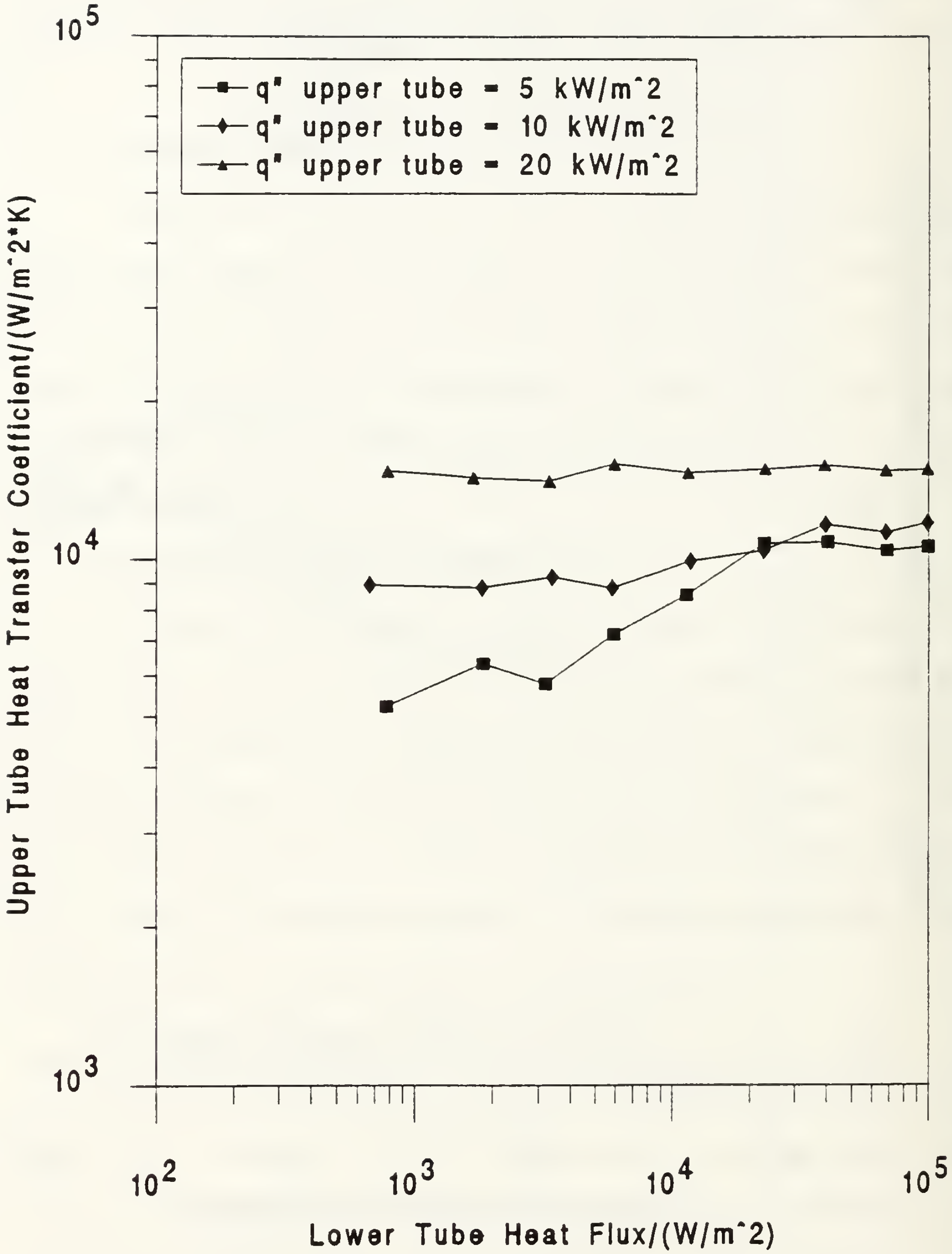

Figure 5.47 Heat Transfer Performance of a TURBO-B Upper Tube at a Constant Heat Flux for a P/D of 1.5

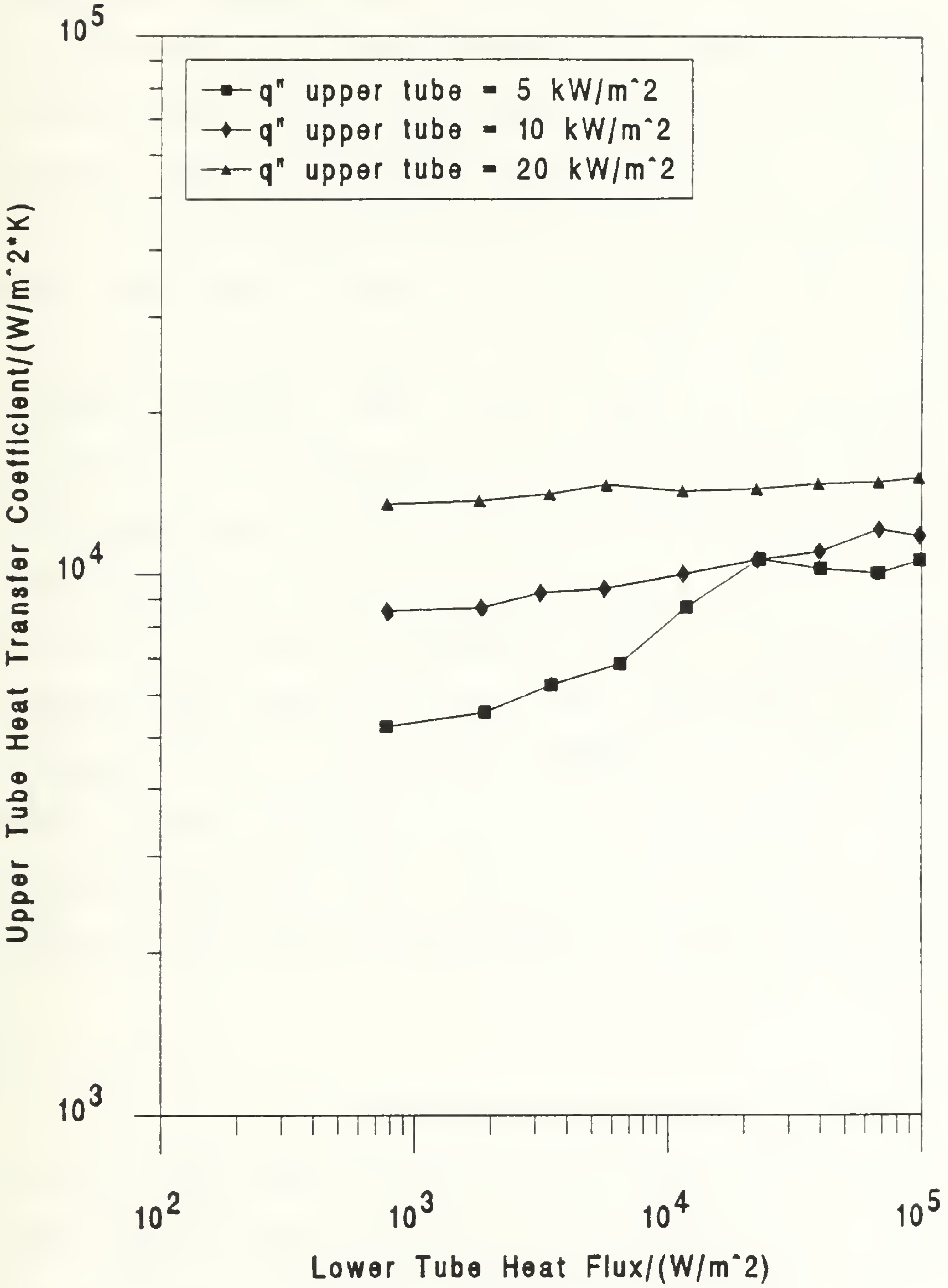

Figure 5.48 Heat Transfer Performance of a TURBO-B Upper Tube at a Constant Heat Flux for a P/D of 1.2

j. TURBO-B Tubes with P/D of 1.2 (Rotated 30°)

Figure 5.49 shows the heat transfer performance of an upper tube, held at a constant heat flux, as the lower tube heat flux is decreased. Comparing Figures 5.48 and 5.49, for an UTHFS of 20 kW/m^2, the data curves are almost identical, indicating that the lower tube orientation and heat flux have very little influence on the upper tube heat transfer behavior. For the other two data curves, the in-line configuration provides better heat transfer performance because of *bubble pumping,* discussed earlier. For the offset configuration, all of the data curves do not merge and are almost horizontal lines, indicating there is no enhancement by *bubble pumping.* It is believed that most of the bubbles coming off the lower tube miss the upper tube because the bubbles depart the TURBO-B tube surface at the upper most section of the tube, which is different than how bubbles depart the smooth tube surface. This phenomena needs to be further investigated. No decreasing curves were recorded for these data runs.

C. R-124/R-114 PERFORMANCE COMPARISON

Figure 5.50 compares the decreasing heat flux data for R-124 found in this study with the R-114 data of Lake [Ref. 3] for smooth tube configurations listed in the plot legend, with the lower tube unheated. In the mid to high heat flux

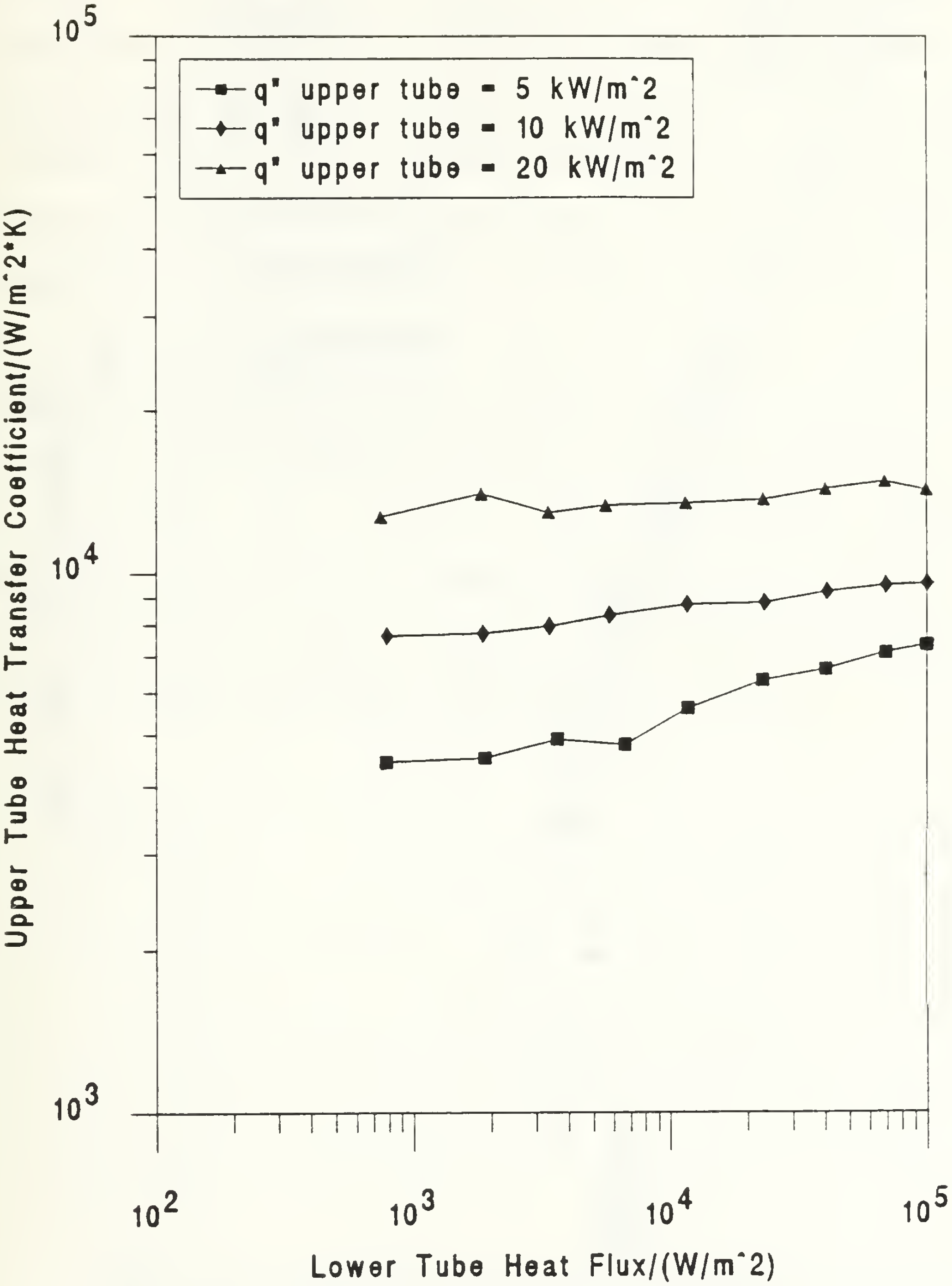

Figure 5.49 Heat Transfer Performance of a TURBO-B Upper Tube at a Constant Heat Flux for a P/D of 1.2 (Rotated 30°)

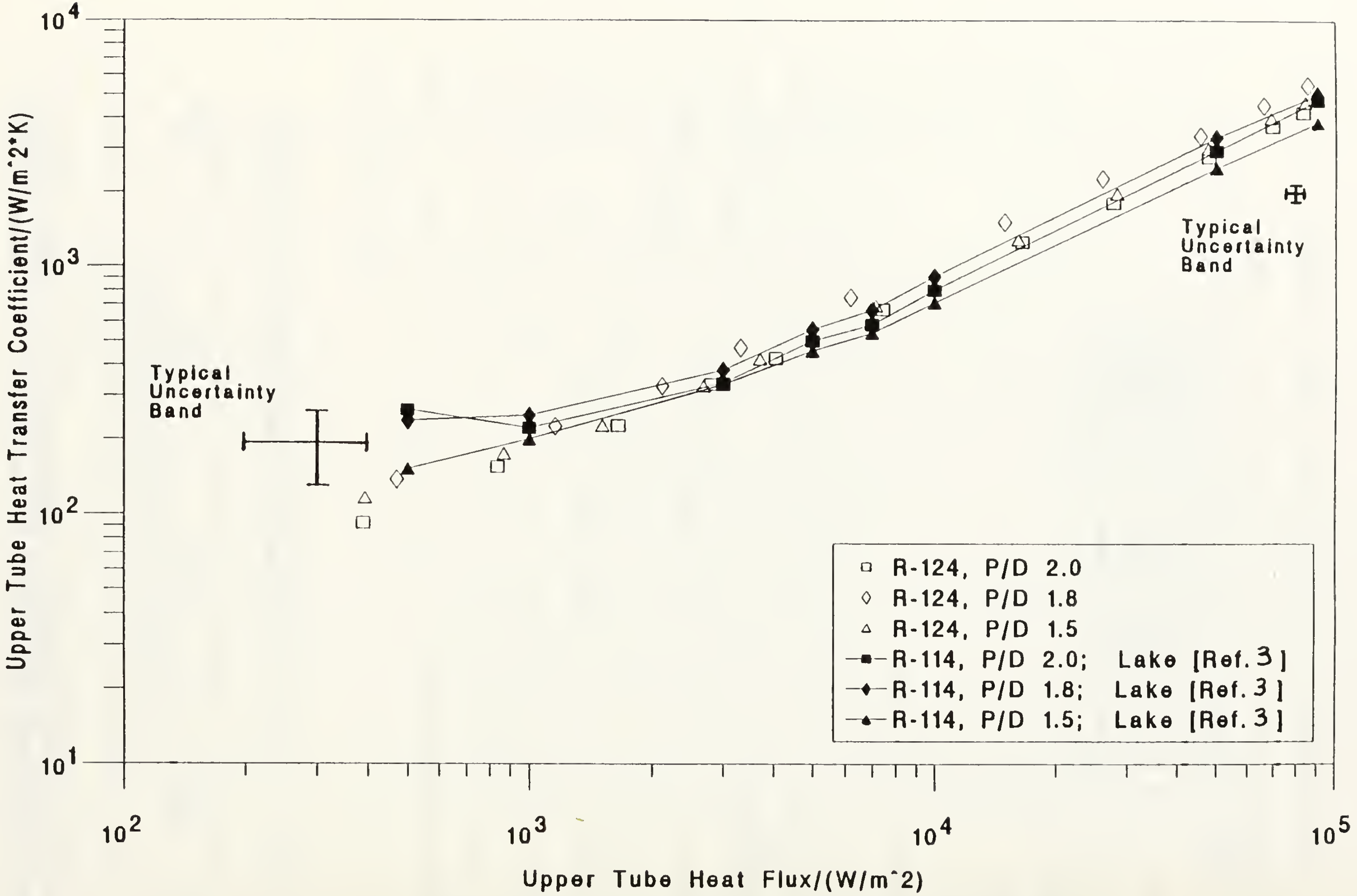

Figure 5.50 Comparison of R-124 to R-114 for Smooth Tubes with Decreasing Heat Flux and the Lower Tube Unheated

regions, the P/D ratios of 1.8 and 1.5 demonstrated improved performance with the R-124, but with a P/D of 2.0, little or no improvement was found. In the low heat flux region, the uncertainty is too large to make any definitive conclusions.

Figure 5.51 compares the decreasing heat flux data for R-124 with the R-114 data of Lake [Ref. 3] for the smooth tube configurations listed in the plot legend, with 10 kW/m^2 on the lower tube. In the high heat flux region, a P/D of 1.8 and 1.5 again provided better performance using R-124, but for R-114, a P/D of 2.0 displayed slightly better performance. In the mid-range heat fluxes, R-114 exhibited improved performance in each of the three configurations. Again, in the low heat flux region, there was too much uncertainty in the data to draw any viable conclusions.

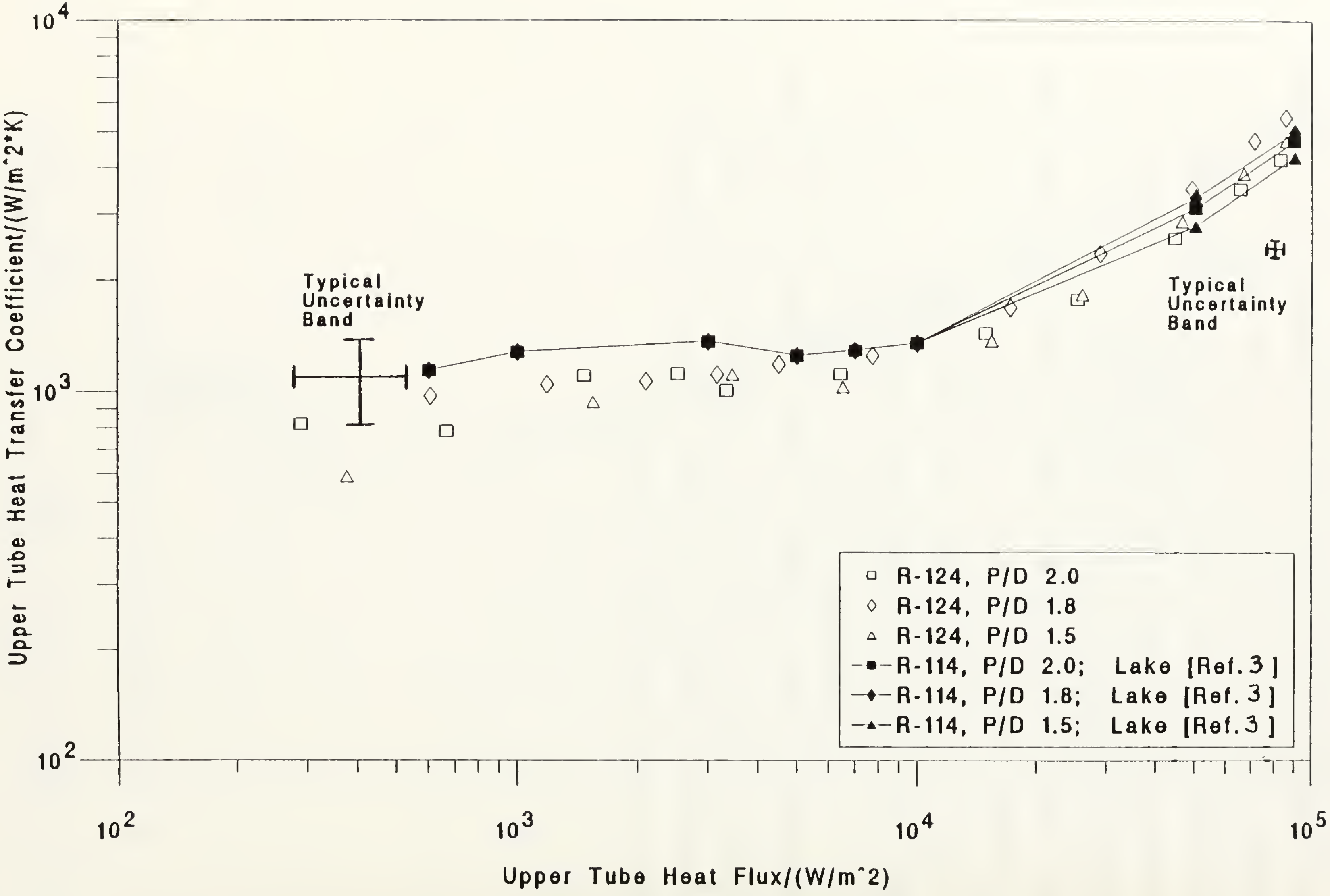

Figure 5.51 Comparison of R-124 to R-114 for Smooth Tubes with Decreasing Heat Flux and a LTHFS of 10 kW/m^2

VI. CONCLUSIONS

The interaction effects of a lower heated tube on pool boiling of R-124 from an upper horizontal tube has been studied for tube two types: smooth and TURBO-B. Based on the data obtained, the following conclusions are made:

1. In natural convection, the effect of a lower heated tube on the heat transfer from an upper tube was small.
2. For a smooth tube array, a vigorously nucleating lower tube eliminated upper tube hysteresis.
3. For a smooth tube array in nucleate boiling, P/D of 1.8 gave the best upper tube heat transfer performance. No optimal P/D was found for the TURBO-B tube array.
4. For both arrays with upper tube heat fluxes < 5 kW/m^2, the enhancing effect of bubbles from a lower tube was dramatic. This enhancement increased as lower tube heat flux increased. When upper tube heat fluxes were > 20 kW/m^2, all enhancement disappeared.
5. For a TURBO-B tube array, a 30 degree offset of the upper tube reduced the upper tube heat transfer performance (compared to the in-line configurations). This may indicate bubbles depart TURBO-B tubes differently than smooth tubes.
6. For a smooth tube array with the lower tube unheated and an upper tube heat flux of > 3 kW/m^2, the performance of R-124 compared to R-114, improved as the P/D ratio was reduced. With a nucleating lower tube (at 10 kW/m^2), again the performance of R-124 improved as the P/D ratio decreased, but only for upper tube heat fluxes of > 40 kW/m^2.

VII. RECOMMENDATIONS

1. Conduct further studies using TURBO-B tubes to verify that bubbles do depart the TURBO-B tubes differently than smooth tubes.

2. Conduct similar tests using different enhanced tubes to better understand the influence of a lower heated enhanced tube on the heat transfer behavior of an upper tube.

3. Modify the existing evaporator to accept a larger number of tubes (three and four smooth or enhanced tubes) and conduct tests to study the effect of multiple heated lower tubes on the heat transfer performance of an upper tube.

4. Conduct similar tests using multiple tube configurations with R-124/oil mixtures to determine the effect of oil on the heat transfer performance of an upper tube.

APPENDIX A. PROGRAM SETUPJY

Program SETUPJY was used to evaluate the system performance prior to commencing a data collection run. This program is written in Hewlett-Packard Basic 5.0 language and enables the operator to:

1. Monitor the coolant sump temperature.
2. Monitor the evaporator liquid pool average temperature.
3. Monitor all the thermocouple channel output temperatures.
4. Monitor the voltage, current and power supplied to the upper tube heater (main heater) as well as the heater element electrical resistance.
5. Monitor the voltage, current and power supplied to the lower tube heater (auxiliary heater) as well as the heater element electrical resistance.

```
10!     PROGRAM: SETUPJY
20!     DATE:    MAY 15, 1993
30!     PROGRAMMER: LT DEAN SUGIYAMA
40!     MODIFIED BY LANNIE LAKE JAN 22, 1992
50!     MODIFIED BY GEORGE D. PERRY 10 APR 1993
60!     MODIFIED BY JOE YUSICIAN MAY 15, 1993
70      COM /Cc/ C(7)
80      DATA 0.10086091,25727.94369,-767345.8295,78025595.81,-9247486589,6.97688E+
11,-2.66192E+13
90      DATA 3.94078E+14
100     READ C(*)
110     ON KEY 1,15 GOTO 150
120     PRINTER IS 1
150     PRINT USING "2X,""SELECT OPTION"""
160     PRINT USING "6X,""0=MONITOR SUMP"""
170     PRINT USING "6X,""1=MONITOR LIQUID"""
180     PRINT USING "6X,""2=CHECK THERMOCOUPLES"""
190     PRINT USING "6X,""3=CHECK MAIN HEATER"""
200     PRINT USING "6X,""4=CHECK AUX HEATERS"""
210     PRINT USING "6X,""5=EXIT PROGRAM"""
230     BEEP
240     INPUT Ido
250     IF Ido>5 THEN Ido=5
260     IF Ido=0 THEN 340
270     IF Ido=1 THEN 520
280     IF Ido=2 THEN 690
290     IF Ido=3 THEN 870
300     IF Ido=4 THEN 870
310     IF Ido=5 THEN 1170
340     PRINT
350     PRINT "SUMP TEMPERATURE DEG C "
360     PRINT
370     OUTPUT 709;"AR AF19 AL19 VR5"
380     OUTPUT 709;"AS SA"
390     Sum=0
400     FOR J=1 TO 5
410     ENTER 709;E
420     Sum=Sum+E
430     NEXT J
440     Eave=Sum/5
450     Temp=FNTvsv(Eave)
460     PRINT USING "4X,MDD.DD";Temp
470     BEEP
480     PRINT
490     WAIT 5
500     GOTO 340
510!
520     PRINT
530     PRINT "LIQUID TEMPERATURE DEG C"
540     PRINT
550     OUTPUT 709;"AR AF16 AL18 VR5"
560     Sum=0
570     FOR I=1 TO 2
580     OUTPUT 709;"AS SA"
590     ENTER 709;E
600     Sum=Sum+E
610     NEXT I
620     Eave=Sum/2
630     Temp=FNTvsv(Eave)
640     PRINT USING "4X,MDD.DD";Temp
650     BEEP
660     WAIT 5
670     GOTO 610
```

```
680!
690    PRINT
700    PRINT "TEMPERATURE         DEG C"
710    OUTPUT 709;"AR AF00 AL19 VR5"
720    FOR I=1 TO 20
730    OUTPUT 709;"AS SA"
740    Sum=0
750    FOR J=1 TO 5
760    ENTER 709;E
770    Sum=Sum+E
780    NEXT J
790    Eave=Sum/5
800    Temp=FNTvsv(Eave)
810    PRINT TAB(3);I;TAB(15);Temp
820    NEXT I
830    BEEP
840    WAIT 5
850    GOTO 690
860!
870    PRINT
880    OUTPUT 709;"AR AF20 AL22 VR5"
890    FOR I=1 TO 3
900    OUTPUT 709;"AS SA"
910    Sum=0
920    FOR J=1 TO 5
930    ENTER 709;E
940    Sum=Sum+E
950    NEXT J
960    IF I=1 THEN Volt=Sum/5
970    IF I=2 AND Ido=3 THEN
980    PRINT "MAKE SURE VOLTAGE BOX IS SET TO MAIN HEATERS"
990    Amp=Sum/5
1000   END IF
1010   IF I=3 AND Ido=4 THEN
1020   PRINT "MAKE SURE VOLTAGE BOX IS SET TO AUX HEATERS"
1030   Amp=Sum/5
1040   END IF
1050   NEXT I
1060   Amp=ABS(Amp*1.9182)
1070   Volt=ABS(Volt*25)
1080   Power=Volt*Amp
1090   Resistence=Volt/Amp
1100   PRINT
1110   BEEP
1120   PRINT "VOLTAGE(V) CURRENT(A) RESISTENCE(ohms) POWER(W)"
1130   PRINT
1140   PRINT USING "1X,5(MDDDD.DD,4X)";Volt,Amp,Resistence,Power
1150   WAIT 5
1160   GOTO 870
1170   BEEP
1180   PRINT
1190   PRINT "SETUP COMPLETE"
1200   END
1210   DEF FNTvsv(V)
1220   COM /Cc/ C(7)
1230   T=C(0)
1240   FOR I=1 TO 7
1250   T=T+C(I)*V^I
1260   NEXT I
1270   T=T+8.626897E-2+T*(3.761199E-3-T*5.0689259E-5)
1280   RETURN T
1290   FNEND
```

APPENDIX B. PROGRAM DRPJY

This data acquisition/reduction program is written in Hewlett-Packard Basic 5.0 language and is listed on the following pages.

```
10   ! FILE NAME: DRPJY
20   ! DATE:       MAY 15, 1993
30   ! REVISED VERSION OF DRP72 FOR R-124 (2 INSTRUMENTED TUBES)
40   ! REVISED BY LT. GEORGE PERRY & LT. JOE YUSICIAN
50     COM /Idp/ Idp
60     PRINTER IS 1
70     CALL Select
80     BEEP
90     PRINT
100    PRINT "DATA COLLECTION COMPLETE"
110    END
120!
130    SUB Main
140    COM /Iprop/ Ift
150    COM /Idp/ Idp
160    COM /Cc/ C(7),Ical
170    COM /Wil/ D2,Di,Do,L,Lu,Kcu
180    DIM Emf(20),T(20),D1a(13),D2a(13),Dia(13),Doa(13),La(13),Lua(13),Kcua(13),
Et(19),Tn$(4)[15]
190    DATA 0.10086091,25727.94369,-767345.8295,78025595.81
200    DATA -9247486589,6.97688E+11,-2.66192E+13,3.94078E+14
210    READ C(*)
220    DATA Smooth,High Flux,Turbo-B,High Flux Mod,Turbo-B Mod
230    READ Tn$(*)
240    PRINTER IS 701
250    PRINT
260    PRINT "           Date :",DATE$(TIMEDATE)
270    PRINT
280    PRINT USING "10X,""NOTE: Program name : DRPJY"""
290    BEEP
300!   INPUT "ENTER INPUT MODE (0=3054A,1=FILE)",Im
310    Im=0
320!   INPUT "SELECT FLUID (0=R-114,1=R-124)",Ift
330    Ift=1
340!   INPUT "1 OR 2 TUBE OPERATION (ENTER 1 OR 2)",Hwmntu
350    Hwmntu=2
360!   INPUT "SELECT HEATING MODE (0=ELEC; 1=WATER)",Ihm
370    Ihm=0
380!   INPUT "ENTER THERMOCOUPLE TYPE (0=NEW,1=OLD)",Ical
390    Ical=0
400    INPUT "GIVE A NAME FOR THE RAW DATA FILE",D2_file$
410    PRINT USING "16X,""New file name: "",15A";D2_file$
420    Size1=20
430    CREATE BDAT D2_file$,Size1
440    ASSIGN @File2 TO D2_file$
450 !
460 ! DUMMY FILE UNTIL Nrun KNOWN
470    D1_file$="DUMMY"
480    CREATE BDAT D1_file$,Size1
490    ASSIGN @File1 TO D1_file$
500    OUTPUT @File1;Date$
510    BEEP
520    INPUT "ENTER NR OF DEFECTIVE UPPER TUBE TCS (0=DEFAULT, 2 MAX.)",Idtc
530    IF Idtc=0 THEN
540    Ldtc1=0
550    Ldtc2=0
560    PRINT USING "16X,""No defective UPPER TUBE TCs exist"""
570    END IF
580    IF Idtc=1 THEN
590    BEEP
600    INPUT "ENTER DEFECTIVE UPPER TUBE TC LOCATION (TEMP 1-8)",Ldtc1
610    PRINT USING "16X,""UPPER TUBE TC is defective at LOCATION:"",DD";Ldtc1
620    Ldtc2=0
630    END IF
640    IF Idtc=2 THEN
650    BEEP
660    INPUT "ENTER DEFECTIVE UPPER TUBE TC LOCATIONS (TEMP 1-8)",Ldtc1,Ldtc2
670    PRINT USING "16X,""UPPER TUBE TC are defective at LOCATIONS:"",DD,4X,DD";L
dtc1,Ldtc2
```

```
680    END IF
690    IF Idtc>2 THEN
700    BEEP
710    PRINTER IS 1
720    BEEP
730    PRINT "INVALID ENTRY"
740    PRINTER IS 701
750    GOTO 510
760    END IF
770    OUTPUT @File1;Ldtc1,Ldtc2
780    IF Hwmntu=1 THEN GOTO 1190
790    INPUT "ENTER NUMBER OF DEFECTIVE LOWER TUBE TCS (0=DEFAULT, 2 MAX)",Aidtc
800    IF Aidtc=0 THEN
810    Aldtc1=0
820    Aldtc2=0
830    PRINT USING "16X,""No defective LOWER TUBE TCs exist"""
840    END IF
850    IF Aidtc=1 THEN
860    BEEP
870    INPUT "ENTER DEFECTIVE TC LOWER TUBE LOCATIONS (TEMP 9-16)",Aldtc1
880    PRINT USING "16X,""LOWER TUBE TC is defective at LOCATION:"",DD";Aldtc1
890    Aldtc2=0
900    END IF
910    IF Aidtc=2 THEN
920    BEEP
930    INPUT "ENTER DEFECTIVE LOWER TUBE TC LOCATIONS (TEMP 9-16)",Aldtc1,Aldtc2
940    PRINT USING "16X,""LOWER TUBE TC are defective at LOCATIONS:"",DD,4X,DD";A
ldtc1,Aldtc2
950    END IF
960    IF Aidtc>2 THEN
970    BEEP
980    PRINTER IS 1
990    BEEP
1000   PRINT "INVALID ENTRY"
1010   PRINTER IS 701
1020   GOTO 790
1030   END IF
1040   OUTPUT @File1;Aldtc1,Aldtc2
1050   PRINTER IS 1
1060   BEEP
1070   PRINT USING "2X,""Select tube number"""
1080   PRINT USING "6X,""4  Wieland Hard 8 inch"""
1090   PRINT USING "6X,""5  HIGH FLUX 8 inch"""
1100!  PRINT USING "6X,""6  GEWA-K 40 Fins/in"""
1110!  PRINT USING "6X,""7  GEWA-K 26 Fins/in"""
1120!  PRINT USING "6X,""8  GEWA-T 19 Fins/in"""
1130!  PRINT USING "6X,""9  GEWA-T OR GEWA-TY 26 Fins/in"""
1140!  PRINT USING "6X,""10 THERMOEXCEL-E"""
1150!  PRINT USING "6X,""11 THERMOEXCEL-HE"""
1160   PRINT USING "6X,""12 TURBO-B"""
1170!  PRINT USING "6X,""13 GEWA-K 19 Fins/in"""
1180   INPUT Itt
1190   OUTPUT @File1;Itt
1200   PRINTER IS 701
1210   IF Itt=4 THEN PRINT USING "16X,""Tubes:  Wieland Hard 8 inch"""
1220   IF Itt=12 THEN PRINT USING "16X,""Tubes:  Turbo-B"""
1230   IF Itt=5 THEN PRINT USING "16X,""Tubes:  High Flux 8 inch"""
1240!  IF Itt<10 THEN PRINT USING "16X,""Tube Number:   "",D";Itt
1250!  IF Itt>9 THEN PRINT USING "16X,""Tube Number:   "",DD";Itt
1260!  INPUT "ENTER OUTPUT VERSION (0=LONG,1=SHORT,2=NONE)",Iov
1270   Iov=0
1280!  INPUT "SELECT (0=LIQ,1=VAP,2=(LIQ+VAP)/2)",Ilqv
1290   Ilqv=2
1300!
1310!  DIMENSIONS FOR TESTED TUBES
1320!
1330!  D1=Diameter at thermocouple positions
1340   DATA .0111125,.0111125,.0111125,.0129540,.012446,.0129540,.0100965
1350   DATA .0100965,.01157,.01157,.01157,.01157,.01157,.0100965
1360   READ D1a(*)
1370   D1=D1a(Itt)
```

```
1380!
1390! D2=Diameter of test section to the base of fins
1400  DATA .015875,.015875,.015875,.015824,.015875,.015824,.01270
1410  DATA .0127,.0138,.0138,.0138,.0138,.0138,.0127
1420  READ D2a(*)
1430  D2=D2a(Itt)
1440!
1450! Di=Inside diameter of unenhanced ends
1460  DATA .0127,.0127,.0127,.0132,.0127,.0132,.0111125,.0111125
1470  DATA .0118,.0118,.0118,.0118,.0118,.0111125
1480  READ Dia(*)
1490  Di=Dia(Itt)
1500!
1510! Do=Outside diameter of unenhanced ends
1520  DATA .015875,.015875,.015875,.015824,.015875,.015824,.01270,.01270
1530  DATA .01331,.01331,.01331,.01331,.0158,.0127
1540  READ Doa(*)
1550  Do=Doa(Itt)
1560!
1570! L=Length of enhanced surface
1580  DATA .1016,.1016,.1016,.1016,.2032,.2032,.2032,.2032,.2032,.2032,.2032,.20
32,.2032,.2032
1590  READ La(*)
1600  L=La(Itt)
1610!
1620! Lu=Length of unenhanced surface at the ends
1630  DATA .0254,.0254,.0254,.0254,.0762,.0762,.0762,.0762,.0762,.0762,.0762,.07
62,.0762,.0762
1640  READ Lua(*)
1650  Lu=Lua(Itt)
1660!
1670! Kcu=Thermal Conductivity of tube
1680  DATA 398,344,344,45,344,45,344,344,398,398,398,398,398,344
1690  READ Kcua(*)
1700  Kcu=Kcua(Itt)
1710!
1720  Xn=.8
1730  Fr=.3
1740  Cf=3.7037E+10
1750  A=PI*(Do^2-Di^2)/4
1760  P=PI*Do
1770  Nsub=0
1780  Ntc=20
1790  J=1
1800 Repeat: !
1810  Dtld=2.22
1820  Ido=2
1830  ON KEY 1,15 RECOVER 1800
1840  PRINTER IS 1
1850  PRINT USING "2X,""SELECT OPTION"""
1860  PRINT USING "6X,""0=TAKE DATA"""
1870  PRINT USING "6X,""1=SET UPPER TUBE HEAT FLUX (MAIN)"""
1880  PRINT USING "6X,""2=SET Tsat"""
1890  PRINT USING "6X,""3=SET LOWER TUBE HEAT FLUX (AUX)"""
1900  BEEP
1910  INPUT Ido
1920  IF Ido>3 THEN Ido=3
1930  IF Ido=0 THEN 3680
1940!
1950! LOOP TO SET UPPER TUBE HEAT FLUX
1960  IF Ido=1 THEN
1970  OUTPUT 709;"AR AF20 AL21 VR5"
1980  PRINT "SET VOLT BOX TO MAIN"
1990  BEEP
2000  INPUT "ENTER DESIRED Qdp",Dqdp
2010  PRINT USING "4X,""DESIRED Qdp  ACTUAL Qdp"""
```

```
2020  Err=1000
2030  FOR I=1 TO 2
2040  OUTPUT 709;"AS SA"
2050  Sum=0
2060  FOR Ji=1 TO 5
2070  ENTER 709;E
2080  Sum=Sum+E
2090  NEXT Ji
2100  IF I=1 THEN Volt=Sum/5
2110  IF I=2 THEN Amp=Sum/5
2120  NEXT I
2130  Amp=ABS(Amp*1.9182)
2140  Volt=ABS(Volt*25)
2150  Aqdp=Volt*Amp/(PI*D2*L)
2160  IF ABS(Aqdp-Dqdp)>Err THEN
2170  IF Aqdp>Dqdp THEN
2180  BEEP 4000,.2
2190  BEEP 4000,.2
2200  BEEP 4000,.2
2210  ELSE
2220  BEEP 250,.2
2230  BEEP 250,.2
2240  BEEP 250,.2
2250  END IF
2260  PRINT USING "4X,MZ.3DE,2X,MZ.3DE";Dqdp,Aqdp
2270  WAIT 2
2280  GOTO 2030
2290  ELSE
2300  BEEP
2310  PRINT USING "4X,MZ.3DE,2X,MZ.3DE";Dqdp,Aqdp
2320  Err=500
2330  WAIT 2
2340  GOTO 2030
2350  END IF
2360  END IF
2370!
2380! LOOP TO SET Tsat
2390  IF Ido=2 THEN
2400  IF Ikdt=1 THEN 2440
2410  Dtld=2.22
2420! PRINT USING "4X,"" DTsat  ATsat   Rate    Tv      Rate"""
2430  Ikdt=1
2440  Old1=0
2450  Old2=0
2460  Nn=1
2470  Nrs=Nn MOD 15
2480  Nn=Nn+1
2490  IF Nrs=1 THEN
2500  PRINT USING "4X,""  Tsat    Tld1    Tld2     Tv    Tsump"""
2510  END IF
2520  OUTPUT 709;"AR AF16 AL19 VR5"
2530  FOR I=1 TO 6
2540  IF I>4 THEN 2700
2550  Sum=0
2560  OUTPUT 709;"AS SA"
2570  FOR Ji=1 TO 20
2580  ENTER 709;Eliq
2590  Sum=Sum+Eliq
2600  NEXT Ji
2610  Eliq=Sum/20
2620  Tld=FNTvsv(Eliq)
2630  IF I=1 THEN Tld1=Tld
2640  IF I=2 THEN Tld2=Tld
2650  IF I=3 THEN Tv=Tld
2660  IF I=4 THEN Tsump=Tld
2670  IF I=5 THEN Tinlet=Tld
2680  IF I=6 THEN Tout=Tld
```

```
2690  NEXT I
2700  Atld=(Tld1+Tld2)*.5
2710  IF ABS(Atld-Dtld)>.2 THEN
2720  IF Atld>Dtld THEN
2730  BEEP 4000,.2
2740  BEEP 4000,.2
2750  BEEP 4000,.2
2760  ELSE
2770  BEEP 250,.2
2780  BEEP 250,.2
2790  BEEP 250,.2
2800  END IF
2810  Err1=Atld-Old1
2820  Old1=Atld
2830  Err2=Tv-Old2
2840  Old2=Tv
2850  IF Tld1>100. THEN 2880
2860  PRINT USING "4X,5(MDD.DD,2X)";Dtld,Tld1,Tld2,Tv,Tsump
2870  WAIT 2
2880  GOTO 2470
2890  ELSE
2900  IF ABS(Atld-Dtld)>.1 THEN
2910  IF Atld>Dtld THEN
2920  BEEP 3000,.2
2930  BEEP 3000,.2
2940  ELSE
2950  BEEP 800,.2
2960  BEEP 800,.2
2970  END IF
2980  Err1=Atld-Old1
2990  Old1=Atld
3000  Err2=Tv-Old2
3010  Old2=Tv
3020  PRINT USING "4X,5(MDDD.DD,2X)";Dtld,Tld1,Tld2,Tv,Tsump
3030  WAIT 2
3040  GOTO 2470
3050  ELSE
3060  BEEP
3070  Err1=Atld-Old1
3080  Old1=Atld
3090  Err2=Tv-Old2
3100  Old2=Tv
3110  PRINT USING "4X,5(MDDD.DD,2X)";Dtld,Tld1,Tld2,Tv,Tsump
3120  WAIT 2
3130  GOTO 2470
3140  END IF
3150  END IF
3160  END IF
3170  !
3180! LOOP TO SET LOWER TUBE HEAT FLUX
3190  IF Ido=3 THEN
3200  PRINT " SET VOLT BOX TO AUX"
3210  OUTPUT 709;"AR AF20 AL22 VR5"
3220  BEEP
3230  INPUT "ENTER DESIRED AuQdp",Duxqdp
3240  PRINT USING "2X,""DESIRED AuxQdp  ACTUAL AuxQdp"""
3250  Err=1000
3260  FOR I=1 TO 3
3270  OUTPUT 709;"AS SA"
3280  Sum=0
3290  FOR Ji=1 TO 5
3300  ENTER 709;E
3310  Sum=Sum+E
3320  NEXT Ji
3330  IF I=1 THEN Volt=Sum/5
3340  IF I=3 THEN Amp=Sum/5
3350  NEXT I
```

```
3360  Amp=ABS(Amp*1.9182)
3370  Volt=ABS(Volt*25)
3380  Auxqdp=Volt*Amp/(PI*D2*L)
3390  IF ABS(Auxqdp-Duxqdp)>Err THEN
3400  IF Auxqdp>Duxqdp THEN
3410  BEEP 4000,.2
3420  BEEP 4000,.2
3430  BEEP 4000,.2
3440  ELSE
3450  BEEP 250,.2
3460  BEEP 250,.2
3470  BEEP 250,.2
3480  END IF
3490  PRINT USING "4X,MZ.3DE,2X,MZ.3DE";Duxqdp,Auxqdp
3500  WAIT 2
3510  GOTO 3260
3520  ELSE
3530  BEEP
3540  PRINT USING "4X,MZ.3DE,2X,MZ.3DE";Duxqdp,Auxqdp
3550  Err=500
3560  WAIT 2
3570  GOTO 3260
3580  END IF
3590  GOTO 1850
3600  END IF
3610! ERROR TRAP FOR Ido OUT OF BOUNDS
3620  IF Ido>3 THEN
3630  BEEP
3640  GOTO 1850
3650  END IF
3660!
3670! TAKE DATA LOOP
3680  IF Ikol=1 THEN 3730
3690  BEEP
3700  Ikol=1
3710  INPUT "ENTER BULK OIL %",Bop
3720  Ikol=1
3730  OUTPUT 709;"AR AF00 AL19 VR5"
3740  Ntc=20
3750  FOR I=1 TO Ntc
3760  OUTPUT 709;"AS SA"
3770  Sum=0
3780  FOR Ji=1 TO 20
3790  ENTER 709;E
3800  Sum=Sum+E
3810  IF I=(17-Nsub) OR I=(18-Nsub) THEN Et(Ji-1)=E
3820  NEXT Ji
3830  Kdl=0
3840  IF I=(17-Nsub) OR I=(18-Nsub) THEN
3850  Eave=Sum/20
3860  Sum=0.
3870  FOR Jk=0 TO 19
3880  IF ABS(Et(Jk)-Eave)<5.0E-6 THEN
3890  Sum=Sum+Et(Jk)
3900  ELSE
3910  Kdl=Kdl+1
3920  END IF
3930  NEXT Jk
3940  IF I=(17-Nsub) OR I=(18-Nsub) THEN PRINT USING "4X,""Kdl = "",DD";Kdl
3950  IF Kdl>20 THEN
3960  BEEP
3970  BEEP
3980  PRINT USING "4X,""Too much scattering in data - repeat data set"""
3990  GOTO 1840
4000  END IF
4010  END IF
4020  Emf(I)=Sum/(20-Kdl)
```

```
4030  NEXT I
4040  Coun=0.
4050  OUTPUT 709;"AR AF20 AL22 VR5"
4060  FOR I=1 TO 3
4070  OUTPUT 709;"AS SA"
4080  Sum=0
4090  FOR Ji=1 TO 5
4100  ENTER 709;E
4110  Sum=Sum+E
4120  NEXT Ji
4130  IF Coun=0. THEN
4140  IF I=1 THEN Vr=Sum/5
4150  IF I=2 THEN Ir=Sum/5
4160  ELSE
4170  IF I=1 THEN Avr=Sum/5
4180  IF I=3 THEN Air=Sum/5
4190  END IF
4200  NEXT I
4210  IF Coun=0 THEN
4220  PRINT "SHIFT VOLT BOX TO AUX"
4230  END IF
4240  IF Coun=1 THEN GOTO 4290
4250  INPUT "TAKE AUX READINGS(1=YES)?",Ccon
4260  IF Ccon>1 THEN GOTO 4250
4270  Coun=Coun+Ccon
4280  GOTO 4060
4290!
4300! CONVERT emf'S TO TEMP,VOLT,CURRENT
4310  Twa=0
4320  Atwa=0
4330  FOR I=1 TO Ntc
4340  IF Idtc>0 THEN
4350  IF I=Ldtc1 OR I=Ldtc2 THEN
4360  T(I)=-99.99
4370  GOTO 4470
4380  END IF
4390  END IF
4400  IF Aidtc>0 THEN
4410  IF I=Aldtc1 OR I=Aldtc2 THEN
4420  T(I)=-99.99
4430  GOTO 4470
4440  END IF
4450  END IF
4460  T(I)=FNTvsv(Emf(I))
4470  NEXT I
4480  Twa=Twa/(4-Idtc)
4490  FOR I=1 TO 8
4500  IF I=Ldtc1 OR I=Ldtc2 THEN
4510  Twa=Twa
4520  ELSE
4530  Twa=Twa+T(I)
4540  END IF
4550  NEXT I
4560  Tw=Twa/(8-Idtc)
4570  FOR I=9 TO 16
4580  IF I=Aldtc1 OR I=Aldtc2 THEN
4590  Atwa=Atwa
4600  ELSE
4610  Atwa=Atwa+T(I)
4620  END IF
4630  NEXT I
4640  Atw=Atwa/(8-Aidtc)
4650  Tld=T(17-Nsub)
4660  Tld2=T(18-Nsub)
4670  Tlda=(Tld+Tld2)*.5
4680  Tv=T(19-Nsub)
4690  Tsump=T(20-Nsub)
```

```
4700  Amp=ABS(Ir*1.9182)
4710  Volt=ABS(Vr)*25
4720  Q=Volt*Amp
4730  Auamp=ABS(Air*1.9182)
4740  Auvolt=ABS(Avr)*25
4750  Auq=Auvolt*Auamp
4760  Kcu=Kcua(Itt)
4770!
4780! FOURIER CONDUCTION EQUATION WITH CONTACT RESISTANCE NEGLECTED
4790  Tw=Tw-Q*LOG(D2/D1)/(2*PI*Kcu*L)
4800  Atw=Atw-Auq*LOG(D2/D1)/(2*PI*Kcu*L)
4810  Tsat=(Tlda+Tv)*.5
4820!
4830! COMPUTE THETHAB
4840  Thetab=Tw-Tsat
4850  Athetab=Atw-Tsat
4860  IF Thetab<0 THEN
4870  BEEP
4880  INPUT "UPPER TWALL<TSAT (0=CONTINUE, 1=END)",Iev
4890  IF Iev=0 THEN GOTO 3150
4900  IF Iev=1 THEN 1850
4910  END IF
4920  IF Athetab<0 THEN
4930  BEEP
4940  INPUT "LOWER TWALL<TSAT (0=CONTINUE, 1=END)",Aiev
4950  IF Aiev=0 THEN GOTO 3150
4960  IF Aiev=1 THEN 1850
4970  END IF
4980!
4990! COMPUTE VARIOUS PROPERTIES
5000  Tfilm=(Tw+Tsat)*.5
5010  Rho=FNRho(Tfilm)
5020  Mu=FNMu(Tfilm)
5030  K=FNK(Tfilm)
5040  Cp=FNCp(Tfilm)
5050  Beta=FNBeta(Tfilm)
5060  Hfg=FNHfg(Tsat)
5070  Ni=Mu/Rho
5080  Alpha=K/(Rho*Cp)
5090  Pr=Ni/Alpha
5100  Psat=FNPsat(Tsat)
5110!
5120! COMPUTE VARIOUS PROPERTIES FOR AUX TUBE
5130  Atfilm=(Atw+Tsat)*.5
5140  Arho=FNRho(Atfilm)
5150  Amu=FNMu(Atfilm)
5160  Ak=FNK(Atfilm)
5170  Acp=FNCp(Atfilm)
5180  Abeta=FNBeta(Atfilm)
5190  Ani=Amu/Arho
5200  Aalpha=Ak/(Arho*Acp)
5210  Apr=Ani/Aalpha
5220!
5230! COMPUTE NATURAL-CONVECTIVE HEAT-TRANSFER COEFFICIENT
5240! FOR UNENHANCED END(S)
5250  Hbar=190
5260  Fe=(Hbar*P/(Kcu*A))^.5*Lu
5270  Tanh=FNTanh(Fe)
5280  Theta=Thetab*Tanh/Fe
5290  Xx=(9.81*Beta*Thetab*Do^3*Tanh/(Fe*Ni*Alpha))^.166667
5300  Yy=(1+(.559/Pr)^(9/16))^(8/27)
5310  Hbarc=K/Do*(.6+.387*Xx/Yy)^2
5320  IF ABS((Hbar-Hbarc)/Hbarc)>.001 THEN
5330  Hbar=(Hbar+Hbarc)*.5
5340  GOTO 5260
5350  END IF
5360!
5370! COMPUTE NATURAL-CONVECTIVE HEAT-TRANSFER COEFFICIENT
5380! FOR UNENHANCED END(S) FOR AUX TUBE
5390  Ahbar=190
5400  Fe=(Ahbar*P/(Kcu*A))^.5*Lu
5410  Atanh=FNTanh(Fe)
```

```
5420  Atheta=Athetab*Atanh/Fe
5430  Axx=(9.81*Abeta*Athetab*Do^3*Atanh/(Fe*Ani*Aalpha))^.166667
5440  Ayy=(1+(.559/Apr)^(9/16))^(8/27)
5450  Ahbarc=Ak/Do*(.6+.387*Axx/Ayy)^2
5460  IF ABS((Ahbar-Ahbarc)/Ahbarc)>.001 THEN
5470  Ahbar=(Ahbar+Ahbarc)*.5
5480  GOTO 5400
5490  END IF
5500!
5510! COMPUTE HEAT LOSS RATE THROUGH UNENHANCED END(S)
5520  Q1=(Hbar*P*Kcu*A)^.5*Thetab*Tanh
5530  Qc=Q-2*Q1
5540  As=PI*D2*L
5550 !
5560 !COMPUTE HEAT LOSS RATE THROUGH UNENHANCED END(S) OF AUX TUBE
5570  Aql=(Ahbar*P*Kcu*A)^.5*Athetab*Atanh
5580  Aqc=Auq-2*Aql
5590!
5600! COMPUTE ACTUAL HEAT FLUX AND BOILING COEFFICIENT
5610  Qdp=Qc/As
5620  Htube=Qdp/Thetab
5630  Csf=(Cp*Thetab/Hfg)/(Qdp/(Mu*Hfg)*(.014/(9.81*Rho)^.5)^(1/3.)*Pr^1.7)
5640!
5650! COMPUTE ACTUAL HEAT FLUX AND BOILING COEFFICIENT FOR AUX TUBE
5660  Auqdp=Aqc/As
5670  Ahtube=Auqdp/Athetab
5680  Acsf=(Acp*Athetab/Hfg)/(Auqdp/(Amu*Hfg)*(.014/(9.81*Arho)^.5)^(1/3.)*Apr^1
.7)
5690!
5700! COMPUTE CHURCHILL-CHU CORRELATION FOR UPPER TUBE
5710  Cc=Hbar*Thetab
5720!
5730! RECORD TIME OF DATA TAKING
5740  OUTPUT 709;"TD"
5750  ENTER 709;Told$
5760!
5770! OUTPUT DATA TO PRINTER
5780  PRINTER IS 701
5790  PRINT
5800  PRINT USING "10X,""Data Set Number = "",DDD,2X,""Bulk Oil % = "",DD.D";J,B
op
5810  PRINT "            TIME:",TIME$(TIMEDATE)
5820  PRINT
5830  PRINT USING "10X,""TC No:    1       2       3       4       5       6       7
   8"""
5840  PRINT USING "10X,""Temp :"",8(1X,MDD.DD)";T(1),T(2),T(3),T(4),T(5),T(6),T(
7),T(8)
5850  PRINT USING "10X,""TC No:    9       10      11      12      13      14      15
    16"""
5860  PRINT USING "10X,""Temp :"",8(1X,MDD.DD)";T(9),T(10),T(11),T(12),T(13),T(1
4),T(15),T(16)
5870  PRINT
5880  PRINT USING "10X,"" Twa   ATwa   Tliqd   Tliqd2  Tvapr  Psat   Tsat   Tsu
mp"""
5890  PRINT USING "10X,3(MDD.DD,1X),1X,MDD.DD,1X,3(1X,MDD.DD),2X,MDD.D";Tw,Atw,T
ld,Tld2,Tv,Psat,Tsat,Tsump
5900  PRINT USING "10X,""    Vr        Ir       Cc"""
5910  PRINT USING "10X,2(MDDD.DD,3X),1X,MZ.3DE";Vr,Ir,Cc
5920  PRINT USING "10X,"" Thetab    Htube      Qdp       Athetab  Ahtube     AuQd
p"""
5930  PRINT USING "10X,MDD.3D,1X,MZ.3DE,1X,MZ.3DE,1X,MDD.3D,1X,MZ.3DE,1X,MZ.3DE"
;Thetab,Htube,Qdp,Athetab,Ahtube,Auqdp
5940  PRINT
5950  BEEP
5960  INPUT "OK TO STORE THIS DATA SET (1=Y,0=N)?",Ok
5970  IF Ok=1 THEN J=J+1
5980  IF Ok=1 AND Im=0 THEN
5990  OUTPUT @File1;Bop,Told$,Emf(*),Vr,Ir,Avr,Air
6000  END IF
6010  IF Iuf=1 THEN OUTPUT @Ufile;Vw,Uo
6020  IF Ire=1 THEN OUTPUT @Refile;Fms,Rew
6030  BEEP
```

```
6040  INPUT "WILL THERE BE ANOTHER RUN (1=Y,0=N)?",Go_on
6050  Nrun=J
6060  IF Go_on=0 THEN 6080
6070  IF Go_on<>0 THEN Repeat
6080  BEEP
6090  PRINT
6100  PRINT USING "10X,""NOTE: "",ZZ,"" data runs were stored in file "",15A";J-
1,D2_file$
6110  ASSIGN @File1 TO *
6120  OUTPUT @File2;Nrun-1
6130  ASSIGN @File1 TO D1_file$
6140  ENTER @File1;Date$,Ldtc1,Ldtc2,Itt
6150  ENTER @File1;Aldtc1,Aldtc2
6160  OUTPUT @File2;Date$,Ldtc1,Ldtc2,Itt
6170  OUTPUT @File2;Aldtc1,Aldtc2
6180  FOR I=1 TO Nrun-1
6190  ENTER @File1;Bop,Told$,Emf(*),Vr,Ir
6200  ENTER @File1;Avr,Air
6210  OUTPUT @File2;Bop,Told$,Emf(*),Vr,Ir
6220  OUTPUT @File2;Avr,Air
6230  NEXT I
6240  ASSIGN @File1 TO *
6250  PRINTER IS 1
6260  PURGE "DUMMY"
6270  PRINT
6280  PRINT "DUMMY FILE PURGED"
6290  SUBEND
6300!
6310! CURVE FITS OF PROPERTY FUNCTIONS
6320!
6330  DEF FNKcu(T)
6340! OFHC COPPER 250 TO 300 K
6350  Tk=T+273.15      !C TO K
6360  K=434-.112*Tk
6370  RETURN K
6380  FNEND
6390!
6400  DEF FNMu(T)
6410  COM /Iprop/ Ift
6420  IF Ift=1 THEN
6430  !223 TO 373 K
6440! 170 TO 360 K CURVE FIT OF VISCOUSITY
6450  Tk=T+273.15      !C TO K
6460  Mu=EXP(-4.4636+(1011.47/Tk))*1.0E-3
6470  END IF
6480  IF Ift=1 THEN
6490! 223 TO 373 K
6500  Mu=3.4593-4.26E-2*T+3.9485E-4*T^2-4.193E-6*T^3+2.0709E-8*T^4
6510  Mu=Mu*1.0E-4
6520  END IF
6530  RETURN Mu
6540  FNEND
6550!
6560  DEF FNCp(T)
6570  COM /Iprop/ Ift
6580  IF Ift=0 THEN
6590! 180 TO 400 K CURVE FIT OF Cp
6600  Tk=T+273.15      !C TO K
6610  Cp=.40188+1.65007E-3*Tk+1.51494E-6*Tk^2-6.67853E-10*Tk^3
6620  Cp=Cp*1000
6630  END IF
6640  IF Ift=1 THEN
6650! 223 TO 373 K CURVE FIT Cp(R124)
6660  Cp=1.0542+2.1405E-3*T+1.0709E-5*T^2-6.4721E-8*T^3-1.4324E-9*T^4+4.136E-11*
T^5
6670  Cp=Cp*1000
6680  END IF
6690  RETURN Cp
6700  FNEND
```

```
6710!
6720  DEF FNRho(T)
6730  COM /Iprop/ Ift
6740  IF Ift=0 THEN
6750  Tk=T+273.15      !C TO K
6760  X=1-(1.8*Tk/753.95)  !K TO R
6770  Ro=36.32+61.146414*X^(1/3)+16.418015*X+17.476838*X^.5+1.119828*X^2
6780  Ro=Ro/.062428
6790  END IF
6800  IF Ift=1 THEN
6810! 223 TO 373 K (R124)
6820  Ro=1434.8-2.8619*T-6.7267E-3*T^2-7.2852E-5*T^3
6830  END IF
6840  RETURN Ro
6850  FNEND
6860!
6870  DEF FNK(T)
6880  COM /Iprop/ Ift
6890  IF Ift=0 THEN
6900! T<360 K WITH T IN C
6910  K=.071-.000261*T
6920  END IF
6930! RETURN K
6940  IF Ift=1 THEN
6950! 223 TO 373 K (R-124)
6960  K=7.5191E-2-3.5436E-4*T-1.9545E-7*T^2+3.1835E-9*T^3
6970  END IF
6980  RETURN K
6990  FNEND
7000!
7010  DEF FNTanh(X)
7020  P=EXP(X)
7030  Q=1/P
7040  Tanh=(P-Q)/(P+Q)
7050  RETURN Tanh
7060  FNEND
7070!
7080  DEF FNTvsv(V)
7090  COM /Cc/ C(7),Ical
7100  T=C(0)
7110  FOR I=1 TO 7
7120  T=T+C(I)*V^I
7130  NEXT I
7140  IF Ical=1 THEN
7150  T=T-6.7422934E-2+T*(9.0277043E-3-T*(-9.3259917E-5))
7160  ELSE
7170  T=T+8.626897E-2+T*(3.76199E-3-T*5.0689259E-5)
7180  END IF
7190  RETURN T
7200  FNEND
7210!
7220  DEF FNBeta(T)
7230  Rop=FNRho(T+.1)
7240  Rom=FNRho(T-.1)
7250  Beta=-2/(Rop+Rom)*(Rop-Rom)/.2
7260  RETURN Beta
7270  FNEND
7280!
7290  DEF FNHfg(T)
7300  COM /Iprop/ Ift
7310  IF Ift=0 THEN
7320  Hfg=1.3741344E+5-T*(3.3094361E+2+T*1.2165143)
7330  END IF
7340  IF Ift=1 THEN
7350! 223 TO 373 K CURVE FIT (R124)
7360  Hfg=159.93-.4609*T-1.458E-3*T^2-1.3715E-5*T^3
7370  Hfg=Hfg*1000
```

```
7380  END IF
7390  RETURN Hfg
7400  FNEND
7410!
7420  DEF FNPsat(Tc)
7430  COM /Iprop/ Ift
7440  IF Ift=0 THEN
7450! 0 TO 80 deg F CURVE FIT OF Psat
7460  Tf=1.8*Tc+32
7470  Pa=5.945525+Tf*(.15352082+Tf*(1.4840963E-3+Tf*9.6150671E-6))
7480  Pg=Pa-14.7
7490  END IF
7500  IF Ift=1 THEN
7510! 223 TO 373 K CURVE FIT (R-124)
7520  Pa=(162.68+5.946*Tc+9.2081E-2*Tc^2+6.9359E-4*Tc^3)*.14504
7530  Pg=Pa-14.7
7540  END IF
7550  IF Pg>0 THEN       ! +=PSIG,-=in Hg
7560  Psat=Pg
7570  ELSE
7580  Psat=Pg*29.92/14.7
7590  END IF
7600  RETURN Psat
7610  FNEND
7620 !
7630 !
7640  SUB Purg
7650  BEEP
7660  INPUT "ENTER FILE NAME TO BE DELETED",File$
7670  PURGE File$
7680  GOTO 7650
7690  SUBEND
7700 !
7710 !
7720  SUB Select
7730  COM /Idp/ Idp
7740  BEEP
7750  PRINTER IS 1
7760  PRINT USING "2X,""Select option:"""
7770  PRINT USING "6X,"" 0 TAKE DATA"""
7780  PRINT USING "6X,"" 1 PURGE FILES"""
7790  INPUT Idp
7800  IF Idp=0 THEN CALL Main
7810  IF Idp=1 THEN CALL Purg
7820  SUBEND
```

APPENDIX C. REPRESENTATIVE DATA SET

```
Date :      7 Sep 1993

NOTE: Program name : DRPJY
      New file name: 00907SC2
      UPPER TUBE TC are defective at LOCATIONS: 7     8
      LOWER TUBE TC is defective at LOCATION: 9
      Tubes:  Wieland Hard 8 inch

Data Set Number =    1  Bulk Oil % =  0.0
TIME:      13:13:35

TC No:      1       2       3       4       5       6       7       8
Temp :    3.85    3.73    3.75    3.56    3.37    3.89  -99.99  -99.99
TC No:      9      10      11      12      13      14      15      16
Temp :  -99.99   20.20   18.36   20.46   19.64   20.49   18.63   17.30

  Twa    ATwa    Tliqd    Tliqd2   Tvapr   Psat    Tsat    Tsump
  3.79   19.36    2.20     2.22     2.11   10.82    2.16   -10.3
     Vr          Ir          Cc
    .84         .17      2.388E+02
 Thetab     Htube       Qdp       Athetab   Ahtube      AuQdp
  1.526   3.408E+02  5.542E+02   17.194   1.832E+02  3.150E+03


Data Set Number =    2  Bulk Oil % =  0.0
TIME:      13:14:38

TC No:      1       2       3       4       5       6       7       8
Temp :    4.37    4.31    4.32    4.32    4.96    5.10  -99.99  -99.99
TC No:      9      10      11      12      13      14      15      16
Temp :  -99.99   20.49   19.22   20.57   20.07   20.32   18.38   17.68

  Twa    ATwa    Tliqd    Tliqd2   Tvapr   Psat    Tsat    Tsump
  4.94   19.65    2.29     2.36     2.18   10.90    2.25   -10.8
     Vr          Ir          Cc
   1.13         .23      4.530E+02
 Thetab     Htube       Qdp       Athetab   Ahtube      AuQdp
  2.688   3.368E+02  1.040E+03   17.397   1.793E+02  3.120E+03


Data Set Number =    3  Bulk Oil % =  0.0
TIME:      13:16:14

TC No:      1       2       3       4       5       6       7       8
Temp :    7.38    7.12    7.12    6.82    7.19    7.43  -99.99  -99.99
TC No:      9      10      11      12      13      14      15      16
Temp :  -99.99   20.08   18.76   20.32   19.41   20.16   18.35   16.96

  Twa    ATwa    Tliqd    Tliqd2   Tvapr   Psat    Tsat    Tsump
  7.17   19.12    2.07     2.13     2.02   10.73    2.06   -10.3
     Vr          Ir          Cc
   1.49         .31      1.025E+03
 Thetab     Htube       Qdp       Athetab   Ahtube      AuQdp
  5.104   3.410E+02  1.740E+03   17.057   1.860E+02  3.172E+03
```

```
Data Set Number =   4  Bulk Oil % =  0.0
TIME:      13:17:49

TC No:     1       2       3       4       5       6       7       8
Temp :  10.40   10.10   10.12    9.64   10.01   10.50  -99.99  -99.99
TC No:     9      10      11      12      13      14      15      16
Temp : -99.99   20.02   18.77   20.12   19.61   20.29   18.32   17.29

  Twa    ATwa    Tliqd    Tliqd2  Tvapr   Psat    Tsat    Tsump
 10.11  19.18    1.95     2.15     1.92  10.66    1.99   -10.7
     Vr          Ir         Cc
   1.87         .39      1.855E+03
 Thetab      Htube       Qdp        Athetab   Ahtube       AuQdp
  8.121   3.319E+02  2.695E+03  17.189   1.834E+02  3.152E+03


Data Set Number =   5  Bulk Oil % =  0.0
TIME:      13:18:54

TC No:     1       2       3       4       5       6       7       8
Temp :  14.37   14.17   14.12   13.47   13.75   14.60  -99.99  -99.99
TC No:     9      10      11      12      13      14      15      16
Temp : -99.99   20.49   19.23   20.42   20.02   20.52   18.47   17.67

  Twa    ATwa    Tliqd    Tliqd2  Tvapr   Psat    Tsat    Tsump
 14.05  19.52    2.01     2.25     2.04  10.76    2.09   -10.6
     Vr          Ir         Cc
   2.36         .50      3.046E+03
 Thetab      Htube       Qdp        Athetab   Ahtube       AuQdp
 11.960   3.630E+02  4.342E+03  17.429   1.780E+02  3.102E+03


Data Set Number =   6  Bulk Oil % =  0.0
TIME:      13:20:03

TC No:     1       2       3       4       5       6       7       8
Temp :  17.69   17.40   17.30   16.51   16.64   17.63  -99.99  -99.99
TC No:     9      10      11      12      13      14      15      16
Temp : -99.99   20.21   18.86   20.32   19.69   20.48   18.47   17.08

  Twa    ATwa    Tliqd    Tliqd2  Tvapr   Psat    Tsat    Tsump
 17.16  19.27    2.04     2.32     2.09  10.80    2.13   -10.7
     Vr          Ir         Cc
   2.58         .55      4.084E+03
 Thetab      Htube       Qdp        Athetab   Ahtube       AuQdp
 15.024   3.379E+02  5.077E+03  17.139   1.834E+02  3.143E+03
```

```
Data Set Number =   7  Bulk Oil % =  0.0
TIME:       13:21:13

TC No:     1       2       3       4       5       6       7       8
Temp :  19.40   19.10   18.35   18.05   18.12   19.37  -99.99  -99.99
TC No:     9      10      11      12      13      14      15      16
Temp : -99.99   19.39   18.74   19.34   19.50   20.11   18.08   17.07

  Twa    ATwa    Tliqd    Tliqd2  Tvapr   Psat    Tsat    Tsump
 18.79  19.03    1.89     2.21     1.96  10.68    2.00   -10.7
     Vr           Ir        Cc
   2.80          .60     4.707E+03
 Thetab     Htube       Qdp        Athetab  Ahtube      AuQdp
 16.783  3.612E+02  6.061E+03  17.027  1.848E+02  3.146E+03


Data Set Number =   8  Bulk Oil % =  0.0
TIME:       13:22:11

TC No:     1       2       3       4       5       6       7       8
Temp :  22.76   22.21   21.96   20.86   21.04   22.51  -99.99  -99.99
TC No:     9      10      11      12      13      14      15      16
Temp : -99.99   19.75   18.48   19.79   19.35   20.05   18.04   16.85

  Twa    ATwa    Tliqd    Tliqd2  Tvapr   Psat    Tsat    Tsump
 21.84  18.87    1.31     2.19     1.90  10.63    1.95   -10.7
     Vr           Ir        Cc
   3.07          .65     5.356E+03
 Thetab     Htube       Qdp        Athetab  Ahtube      AuQdp
 19.389  3.552E+02  7.263E+03  16.325  1.364E+02  3.155E+03


Data Set Number =   9  Bulk Oil % =  0.0
TIME:       13:23:55

TC No:     1       2       3       4       5       6       7       8
Temp :  26.91   26.51   26.32   25.12   24.95   26.71  -99.99  -99.99
TC No:     9      10      11      12      13      14      15      16
Temp : -99.99   20.53   19.25   20.45   20.10   20.75   18.59   17.71

  Twa    ATwa    Tliqd    Tliqd2  Tvapr   Psat    Tsat    Tsump
 26.03  19.60    2.14     2.47     2.23  10.92    2.27   -10.7
     Vr           Ir        Cc
   3.28          .70     7.369E+03
 Thetab     Htube       Qdp        Athetab  Ahtube      AuQdp
 23.757  3.391E+02  8.056E+03  17.328  1.785E+02  3.094E+03
```

```
Data Set Number =  10  Bulk Oil % =  0.0
TIME:      13:27:26

TC No:     1        2        3        4        5        6        7        8
Temp :  10.92   11.50   11.27   11.74   11.29   10.85  -99.99  -99.99
TC No:     9       10       11       12       13       14       15       16
Temp : -99.99   17.36   15.38   17.50   17.07   18.05   16.48   14.36

  Twa    ATwa    Tliqd    Tliqd2   Tvapr   Psat    Tsat    Tsump
 11.16   16.54    2.25     2.25     2.09   10.33    2.17   -10.6
     Vr          Ir          Cc
   3.79         .81      2.114E+03
 Thetab      Htube          Qdp         Athetab   Ahtube       AuQdp
  8.991   1.510E+03  1.357E+04   14.471   2.455E+02   3.553E+03

Data Set Number =  11  Bulk Oil % =  0.0
TIME:      13:29:22

TC No:     1        2        3        4        5        6        7        8
Temp :  11.77   12.52   12.23   12.73   12.40   11.31  -99.99  -99.99
TC No:     9       10       11       12       13       14       15       16
Temp : -99.99   16.30   15.33   16.98   16.60   17.31   16.36   13.76

  Twa    ATwa    Tliqd    Tliqd2   Tvapr   Psat    Tsat    Tsump
 12.14   16.21    2.23     2.22     2.01   10.78    2.12   -10.6
     Vr          Ir          Cc
   4.48         .96      2.430E+03
 Thetab      Htube          Qdp         Athetab   Ahtube       AuQdp
 10.027   1.924E+03  1.929E+04   14.092   4.218E+02   5.944E+03

Data Set Number =  12  Bulk Oil % =  0.0
TIME:      13:30:20

TC No:     1        2        3        4        5        6        7      - 8
Temp :  13.80   14.46   14.14   14.73   14.52   13.94  -99.99  -99.99
TC No:     9       10       11       12       13       14       15       16
Temp : -99.99   16.21   14.70   16.26   15.95   17.07   15.51   13.21

  Twa    ATwa    Tliqd    Tliqd2   Tvapr   Psat    Tsat    Tsump
 14.07   15.53    2.11     2.14     1.93   10.70    2.03   -10.6
     Vr          Ir          Cc
   5.88        1.25      3.072E+03
 Thetab      Htube          Qdp         Athetab   Ahtube       AuQdp
 12.039   2.792E+03  3.361E+04   13.502   2.755E+02   3.720E+03
```

```
Data Set Number =  13  Bulk Oil % =  0.0
TIME:      13:31:43

TC No:     1       2       3       4       5       6       7       8
Temp :  16.12   16.75   16.45   17.02   16.37   16.17  -99.99  -99.99
TC No:     9      10      11      12      13      14      15      16
Temp : -99.99   15.79   14.44   15.37   15.71   16.93   15.49   13.23

  Twa    ATwa    Tliqd    Tliqd2  Tvapr   Psat    Tsat    Tsump
 16.24  15.34    2.21     2.32     2.16  10.37    2.21   -10.6
     Vr          Ir         Cc
   7.71        1.64     3.739E+03
 Thetab     Htube       Qdp        Athetab   Ahtube      AuQdp
 14.030  4.162E+03  5.339E+04  13.125  2.363E+02  3.766E+03


Data Set Number =  14  Bulk Oil % =  0.0
TIME:      13:32:48

TC No:     1       2       3       4       5       6       7       8
Temp :  17.77   18.27   17.33   18.48   18.59   17.70  -99.99  -99.99
TC No:     9      10      11      12      13      14      15      16
Temp : -99.99   15.53   14.22   15.56   15.39   15.51   14.99   12.90

  Twa    ATwa    Tliqd    Tliqd2  Tvapr   Psat    Tsat    Tsump
 17.64  15.03    2.29     2.36     2.21  10.92    2.27   -10.6
     Vr          Ir         Cc
   8.23        1.86     4.207E+03
 Thetab     Htube       Qdp        Athetab   Ahtube      AuQdp
 15.375  5.453E+03  9.384E+04  12.760  2.372E+02  3.792E+03


Data Set Number =  15  Bulk Oil % =  0.0
TIME:      13:34:20

TC No:     1       2       3       4       5       6       7     - 8
Temp :  16.36   17.52   17.20   17.74   17.69   16.30  -99.99  -99.99
TC No:     9      10      11      12      13      14      15      16
Temp : -99.99   15.59   14.13   15.38   15.39   16.64   15.18   12.94

  Twa    ATwa    Tliqd    Tliqd2  Tvapr   Psat    Tsat    Tsump
 16.35  15.05    2.40     2.54     2.31  11.03    2.39   -10.4
     Vr          Ir         Cc
   8.23        1.75     3.925E+03
 Thetab     Htube       Qdp        Athetab   Ahtube      AuQdp
 14.563  4.572E+03  6.658E+04  12.562  2.387E+02  3.782E+03
```

```
Data Set Number =  16  Bulk Oil % =  0.0
TIME:      13:35:45

TC No:     1       2       3       4       5       6       7       8
Temp :   15.51   16.29   15.38   15.59   16.32   15.60  -99.99  -99.99
TC No:     9      10      11      12      13      14      15      16
Temp :  -99.99   15.49   14.01   15.51   15.31   16.33   14.36   12.72

  Twa    ATwa    Tliqd    Tliqd2  Tvapr  Psat    Tsat    Tsump
 15.80  14.36    2.33     2.35    2.25  10.94    2.29   -10.4
     Vr          Ir         Cc
   5.38        1.47      3.560E+03
 Thetab     Htube        Qdp        Athetab  Ahtube      AuQdp
 13.503  3.431E+03  4.634E+04  12.568  3.038E+02  3.818E+03

Data Set Number =  17  Bulk Oil % =  0.0
TIME:      13:36:51

TC No:     1       2       3       4       5       6       7       8
Temp :   13.76   14.46   14.18   14.81   14.21   13.65  -99.99  -99.99
TC No:     9      10      11      12      13      14      15      16
Temp :  -99.99   15.21   13.75   15.17   15.10   16.15   14.60   12.42

  Twa    ATwa    Tliqd    Tliqd2  Tvapr  Psat    Tsat    Tsump
 14.02  14.60    2.25     2.29    2.08  10.83    2.17   -10.2
     Vr          Ir         Cc
   5.28        1.13      3.010E+03
 Thetab     Htube        Qdp        Athetab  Ahtube      AuQdp
 11.848  2.271E+03  2.630E+04  12.427  3.095E+02  3.347E+03

Data Set Number =  18  Bulk Oil % =  0.0
TIME:      13:38:09

TC No:     1       2       3       4       5       6       7       8
Temp :   11.86   12.64   12.42   12.98   12.20   11.69  -99.99  -99.99
TC No:     9      10      11      12      13      14      15      16
Temp :  -99.99   15.29   13.82   15.28   15.25   16.45   15.07   12.61

  Twa    ATwa    Tliqd    Tliqd2  Tvapr  Psat    Tsat    Tsump
 12.21  14.80    2.28     2.24    2.06  10.82    2.16   -10.1
     Vr          Ir         Cc
   4.06         .87      2.437E+03
 Thetab     Htube        Qdp        Athetab  Ahtube      AuQdp
 10.048  1.556E+03  1.563E+04  12.638  3.005E+02  3.797E+03
```

```
Data Set Number =  19  Bulk Oil % =  0.0
TIME:      13:39:28

TC No:     1       2       3       4       5       6       7       8
Temp :    9.20    9.58    9.45    9.30    9.35    9.39  -99.99  -99.99
TC No:     9      10      11      12      13      14      15      16
Temp : -99.99   15.63   14.21   15.46   15.66   16.68   15.32   13.16

  Twa    ATwa    Tliqd    Tliqd2  Tvapr  Psat    Tsat    Tsump
  9.50  15.13    2.28     2.35    2.17  10.30    2.24   -10.1
     Vr          Ir         Cc
   2.72         .58      1.609E+03
 Thetab     Htube       Qdp        Athetab   Ahtube      AuQdp
  7.251  9.245E+02  6.712E+03  12.890  2.368E+02  3.696E+03


Data Set Number =  20  Bulk Oil % =  0.0
TIME:      13:40:18

TC No:     1       2       3       4       5       6       7       8
Temp :    7.12    7.13    7.03    7.10    7.79    7.23  -99.99  -99.99
TC No:     9      10      11      12      13      14      15      16
Temp : -99.99   15.65   14.29   15.45   15.38   16.67   15.31   13.21

  Twa    ATwa    Tliqd    Tliqd2  Tvapr  Psat    Tsat    Tsump
  7.21  15.15    2.25     2.32    2.22  10.91    2.25   -10.1
     Vr          Ir         Cc
   2.04         .43      8.873E+02
 Thetab     Htube       Qdp        Athetab   Ahtube      AuQdp
  4.956  7.498E+02  3.717E+03  12.900  2.322E+02  3.769E+03


Data Set Number =  21  Bulk Oil % =  0.0
TIME:      13:41:00

TC No:     1       2       3       4       5       6       7       8
Temp :    6.17    6.12    6.04    6.02    5.77    6.33  -99.99  -99.99
TC No:     9      10      11      12      13      14      15      16
Temp : -99.99   15.78   14.52   15.68   15.39   16.76   15.50   13.48

  Twa    ATwa    Tliqd    Tliqd2  Tvapr  Psat    Tsat    Tsump
  6.23  15.34    2.29     2.36    2.25  10.94    2.29   -10.0
     Vr          Ir         Cc
   1.74         .37      7.367E+02
 Thetab     Htube       Qdp        Athetab   Ahtube      AuQdp
  3.336  6.801E+02  2.577E+03  13.053  2.368E+02  3.744E+03
```

```
Data Set Number =  22  Bulk Oil % =  0.0
TIME:      13:42:13

TC No:     1       2       3       4       5       6       7       8
Temp :   4.38    4.40    4.39    4.37    4.33    4.51  -99.99  -99.99
TC No:     9      10      11      12      13      14      15      16
Temp : -99.99   15.98   14.70   15.33   16.07   16.36   15.58   13.55

  Twa    ATwa    Tliqd    Tliqd2  Tvapr   Psat    Tsat    Tsump
  4.47  15.51    2.45     2.51     2.35   11.06    2.41   -10.1
     Vr          Ir         Cc
   1.33         .27      3.225E+02
 Thetab     Htube        Qdp        Athetab   Ahtube      AuQdp
  2.058  7.640E+02  1.572E+03  13.095  2.868E+02  3.755E+03


Data Set Number =  23  Bulk Oil % =  0.0
TIME:      13:43:07

TC No:     1       2       3       4       5       6       7       8
Temp :   3.58    3.53    3.52    3.47    3.83    3.50  -99.99  -99.99
TC No:     9      10      11      12      13      14      15      16
Temp : -99.99   15.38   14.54   15.88   15.98   16.39   15.54   13.42

  Twa    ATwa    Tliqd    Tliqd2  Tvapr   Psat    Tsat    Tsump
  3.58  15.42    2.31     2.37     2.19   10.92    2.27   -10.0
     Vr          Ir         Cc
    .99         .20      1.825E+02
 Thetab     Htube        Qdp        Athetab   Ahtube      AuQdp
  1.317  6.529E+02  8.597E+02  13.153  2.808E+02  3.693E+03


Data Set Number =  24  Bulk Oil % =  0.0
TIME:      13:44:32

TC No:     1       2       3       4       5       6       7     _ 8
Temp :   2.36    2.34    2.95    2.33    3.12    2.99  -99.99  -99.99
TC No:     9      10      11      12      13      14      15      16
Temp : -99.99   15.99   14.63   15.87   16.08   17.01   15.68   13.60

  Twa    ATwa    Tliqd    Tliqd2  Tvapr   Psat    Tsat    Tsump
  2.38  15.52    2.46     2.48     2.34   11.05    2.40   -10.0
     Vr          Ir         Cc
    .70         .14      6.344E+01
 Thetab     Htube        Qdp        Athetab   Ahtube      AuQdp
   .574  7.393E+02  4.241E+02  13.120  2.847E+02  3.735E+03


NOTE: 24 data runs were stored in file D0907SCZ
```

APPENDIX D. SAMPLE CALCULATIONS[3]

Data file D0921ASC4 was used for sample calculations. The saturation temperature was 2.2 °C with a heat flux of 59,130 W/m^2 on the smooth upper test tube.

A. SMOOTH TEST TUBE DIMENSIONS

Do = 0.015875 m

Di = 0.0127 m

D1 = 0.012446 m

L = 0.2032 m

Lu = 0.0762 m

B. MEASURED PARAMETERS

$V = Vr \cdot 25 = (7.76\ V)(25) = 194.0\ V$

$I = Ir \cdot 1.9182 = (1.66\ A)(1.9182) = 3.18\ A$

T1 = 19.44 °C T2 = 20.03 °C

T3 = 19.75 °C T4 = 19.63 °C

T5 = 19.46 °C T6 = 19.38 °C

T7 and T8 not used, defective

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[3] This analysis is essentially identical to the analysis done by Perry [Ref. 2] and therefore his procedure is largely reproduced.

$T_{sat} = 2.20$ °C

$k_c = 344$ W/m·K

C. OUTER WALL TEMPERATURE OF THE UPPER TEST TUBE

1. Surface Area of Smooth Tube

$P = \pi \cdot Do = \pi(0.015875\ m) = 0.04987\ m$

$Ac = \pi(Do^2-Di^2)/4 = \pi((0.015875\ m)^2-(0.0127)^2)/4$

$Ac = 7.13 \times 10^{-5}\ m^2$

2. Heater Power

$Qh = V \cdot I = (194.0\ V)(3.18\ A) = 616.92\ W$

3. Average Inside Tube Temperature

$Tavg = \Sigma_1^m\ Tn/m = \Sigma_1^6\ Tn/6 = (T1+T2+T3+T4+T5+T6)/6$

$Tavg = (19.44+20.03+19.75+19.63+19.46+19.38)/6$

$= 19.62$ °C

4. Outside Wall Tube Temperature

Two is calculated using Fourier's Conduction Law, assuming uniform radial conduction and using a known Tavg:

$Two = Tavg - \{Qh(\ln(Do/Di))/(2\pi \cdot L \cdot kc)\}$

$Two = 19.62-\{616.92(\ln(0.015875/0.01245))/$

$(2\pi \cdot 0.203 \cdot 344\ )\}$

$Two = 19.28$ °C

5. Tube Wall Superheat

$\theta = Two - Tsat = 19.28 - 2.20 = 17.08$ °C

D. R-124 PROPERTIES AT FILM TEMPERATURE

The thermophysical properties of R-124 were computed at the film temperature using the REFPROP equations provided by Bertsch [Ref. 1]:

1. Film Temperature

$$Tf = (Two + Tsat)/2 = (19.28 + 2.20)/2 = 10.74\ ^{\circ}C$$

2. Dynamic Viscosity

$$\mu = 3.4593-(0.0426)Tf+(3.9485x10^{-4})Tf^{2}-(4.193x10^{-6})Tf^{3}+ (2.0709x10^{-8})Tf^{4}$$

$$\mu = \{3.4593-(0.0426)10.74+(3.9485x10^{-4})(10.74)^{2}- (4.193x10^{-6})(10.74)^{3}+(2.0709x10^{-8})(10.74)^{4}\}x10^{-4}$$

$$\mu = 3.0424x10^{-4}\ N\cdot s/m^{2}$$

3. Density

$$\rho = 1434.8-(2.8619)Tf-(6.7267x10^{-3})Tf^{2}-(7.2852x10^{-5})Tf^{3}$$

$$\rho = 1434.8-(2.8619)10.74-(6.7267x10^{-3})(10.74)^{2}- (7.2852x10^{-5})(10.74)^{3}$$

$$\rho = 1403.2\ kg/m^{3}$$

4. Kinematic Viscosity

$$\nu = \mu/\rho = 3.0422x10^{-4}/1403.2 = 2.17x10^{-7}\ m/s$$

5. Thermal Conductivity

$$k = 7.5191x10^{-2}-(3.5436x10^{-4})Tf-(1.9545x10^{-7})Tf^{2}+ (3.1835x10^{-9})Tf^{3}$$

$$k = 7.5191x10^{-2}-(3.5436x10^{-4})(10.74)-(1.9545x10^{-7}) (10.74)^{2}+(3.1835x10^{-9})(10.74)^{3}$$

$$k = 7.137x10^{-2}\ W/m\cdot K$$

6. Specific Heat

$$Cp = 1.0542+(2.1405\times10^{-3})Tf+(1.0709\times10^{-5})Tf^2-(6.4721\times10^{-8})\cdot Tf^3-(1.4324\times10^{-9})Tf^4+(4.136\times10^{-11})Tf^5$$

$$Cp = \{1.0542+(2.1405\times10^{-3})(10.74)+(1.0709\times10^{-5})(10.74)^2-(6.4721\times10^{-8})(10.74)^3-(1.4324\times10^{-9})(10.74)^4+(4.136\times10^{-11})(10.74)^5\}\times10^3$$

$$Cp = 1078.35 \text{ J/kg}\cdot\text{K}$$

7. Thermal Diffusivity

$$\alpha = k/(\rho\cdot Cp) = 7.137\times10^{-2}/(1403.2\cdot1078.35)$$

$$\alpha = 4.717\times10^{-8} \text{ m}^2/\text{s}$$

8. Volumetric Thermal Expansion Coefficient

$$\beta = -\Delta\rho/(\rho\cdot\Delta Tf) = -(1402.89-1403.50)/(1403.2\cdot0.2)$$

$$\beta = 2.174\times10^{-3} \quad (1/K)$$

9. Prandtl Number

$$Pr = \nu/\alpha = 2.17\times10^{-7}/4.717\times10^{-8} = 4.60$$

E. HEAT FLUX THROUGH NON-BOILING TUBE LENGTHS

Using the Churchill-Chu correlation [Ref. 9] for a smooth cylinder in natural convection, the average natural convection heat transfer coefficient of one non-boiling tube length is:

$$h = k/Do\{0.6+0.387[\Gamma/(1+(0.559/Pr)^{9/16})^{8/27}]\}^2$$

where $\Gamma = \{[g\cdot\beta\cdot Do^3\cdot\theta\cdot\tanh(m\cdot Lu)]/(\nu\cdot\alpha\cdot Lu\cdot m)\}^{1/6}$

$m = \{(h\cdot P)/(kc\cdot Ac)\}^{1/2}$

The program DRPJY computes the value of h by assuming a starting value of 190 $W/m^2 \cdot K$ and iterating to the final value. The resulting values of h and m are:

$h = 281.93\ W/m^2 \cdot K$

$m = 23.94\ (1/m)$

therefore,

$Qf = (h \cdot p \cdot kc \cdot Ac)^{1/2} \cdot \theta \cdot \tanh(m \cdot Lu) = 9.52\ W$

F. HEAT FLUX THROUGH BOILING TUBE LENGTH

$Q = Qh - 2 \cdot Qf = 616.92 - 2(9.52) = 597.88\ W$

$Ab = \pi \cdot Do \cdot L = \pi (0.015875)(.2032) = 1.013 \times 10^{-2}\ m^2$

$q'' = Q/Ab = 597.88/1.013 \times 10^{-2} = 59,021\ W/m^2$

$h = q''/\theta = 59021/17.08 = 3456\ W/m^2 \cdot K$

The following results were calculated by the data acquisition and reduction program DRPJY:

$q'' = 59,130\ W/m^2$

$h = 3463\ W/m^2 \cdot K$

$\theta = 17.08\ ^\circ C$

APPENDIX E. UNCERTAINTY ANALYSIS[4]

The same data run used for the sample calculations (Appendix D) was used for the uncertainty analysis, thus all the measured and most of the calculated results still apply. A lower heat flux of 1561 W/m^2 was also analyzed from the same data run to show the difference between the two heat fluxes. All uncertainties are presented as a percentage of the calculated parameter, i.e. a relative uncertainty. The uncertainty analysis method suggested by Kline and McClintock [Ref. 29] was used. For example: If R = R($x_1, x_2, x_3, \ldots\ldots x_n$), then:

$$\delta R = \left[\left(\frac{\delta R}{\delta x_1}\delta X_1\right)^2 + \left(\frac{\delta R}{\delta x_2}\delta X_2\right)^2 + \ . \ . \ . \ + \left(\frac{\delta R}{\delta x_3}\delta X_3\right)^2\right]^{\frac{1}{2}}$$

where:

δR = uncertainty of the desired dependent variable

x_n = measured variable

δx_n = uncertainty in the measured variable

---

[4] This analysis is essentially identical to the analysis done by Perry [Ref. 2] and therefore his procedure is largely reproduced.

A. HEAT TRANSFER RATE UNCERTAINTY

Ir = 1.66 amps δIr = 0.025 amps

Vr = 7.76 volts δVr = 0.05 volts

so we have:

$$\frac{\delta Qh}{Qh} = \left[\left(\frac{\delta Vr}{Vr}\right)^2 + \left(\frac{\delta Ir}{Ir}\right)^2\right]^{\frac{1}{2}}$$

$$\frac{\delta Qh}{Qh} = \left[\left(\frac{0.05}{7.76}\right)^2 + \left(\frac{0.025}{1.66}\right)^2\right]^{\frac{1}{2}} = 1.64\%$$

B. SURFACE AREA UNCERTAINTY

The following dimensions were taken from the manufacturer's data sheet, and from actual measurements:

Do = 15.88 (mm) δDo = 0.1 (mm)

L = 203.2 (mm) δL = 0.1 (mm)

Ab = Do x L

$$\frac{\delta Ab}{Ab} = \left[\left(\frac{\delta Do}{Do}\right)^2 + \left(\frac{\delta L}{L}\right)^2\right]^{\frac{1}{2}}$$

$$\frac{\delta Ab}{Ab} = \left[\left(\frac{0.1}{15.88}\right)^2 + \left(\frac{0.1}{203.2}\right)^2\right]^{\frac{1}{2}} = 0.63\%$$

C. WALL SUPERHEAT UNCERTAINTY

The following temperatures were measured:

T1 = 19.44 °C

T2 = 20.03 °C

T3 = 19.75 °C

T4 = 19.63 °C

T5 = 19.46 °C

T6 = 19.38 °C

Tavg = 19.62 °C

Standard Deviation = 0.245 °C

Tsat = 2.20 °C and δTsat = 0.01 °C

$$Two = Tavg - Qh\left[\frac{\ln\left(\frac{Do}{D1}\right)}{2\pi \cdot L \cdot kc}\right]$$

Note: The second term on the right hand side of the above equation is the Fourier heat transfer conduction term, and can be neglected for the uncertainty analysis since its value is less than the standard deviation, so:

Two = Tavg = 19.62 °C

ΔT = Two - Tsat = 19.62 °C - 2.20 °C = 17.42 °C therefore,

$$\frac{\delta \Delta T}{\Delta T} = \left[\left(\frac{\delta \Delta Two}{\Delta T}\right)^2 + \left(\frac{\delta Tsat}{\Delta T}\right)^2\right]^{\frac{1}{2}}$$

$$\frac{\delta \Delta T}{\Delta T} = \left[\left(\frac{0.245}{17.42}\right)^2 + \left(\frac{0.01}{17.42}\right)^2\right]^{\frac{1}{2}} = 1.41\%$$

D. HEAT FLUX UNCERTAINTY

$$q'' = \frac{(Qh - 2 \times Qf)}{Ab}$$

where: $Qh = V \times I = (194\ V)(3.18\ A) = 616.92\ W$

and $\delta Qh = (616.92)(0.0164) = 10.12\ W$

$q'' = 59130\ W/m^2$ (measured)

$Ab = 0.010137\ m^2$

$Qh - 2.Qf = (q)(Ab) = (59130)(0.010137) = 599.40\ W$

solving for Qf:

$Qf = (616.92 - 599.40)/2 = 8.76\ W$

assuming the same proportion uncertainty for Qf, we have:

$\delta Qf = (8.76)(0.0164) = 0.144\ W$

and for the uncertainty:

$$\frac{\delta q''}{q''} = \left[\left(\frac{\delta Qh}{Qh - 2Qf}\right)^2 + \left(\frac{2\delta Qf}{Qh - 2Qf}\right)^2 + \left(\frac{\delta Ab}{Ab}\right)^2\right]^{\frac{1}{2}}$$

$$\frac{\delta q''}{q''} = \left[\left(\frac{10.12}{599.4}\right)^2 + \left(\frac{2 \times 0.144}{599.4}\right)^2 + (0.0063)^2\right]^{\frac{1}{2}} = 1.80\%$$

E. HEAT TRANSFER COEFFICIENT UNCERTAINTY

$$h = q''/\Delta T$$

therefore,

$$\frac{\delta h}{h} = \left[\left(\frac{\delta q''}{q''}\right)^2 + \left(\frac{\delta \Delta T}{\Delta T}\right)^2\right]^{\frac{1}{2}}$$

$$\frac{\delta h}{h} = [(0.018)^2 + (0.0141)^2]^{\frac{1}{2}} = 2.29\%$$

The above series of calculations was also conducted with a lower heat flux for the same data run and with a high and low heat flux from a TURBO-B data run (D1022FTBC4) with the results tabulated in Table 5.

TABLE 5. RESULTS OF UNCERTAINTY ANALYSIS

PARAMETER	SMOOTH 1561 W/m^2	SMOOTH 59130 W/m^2	TURBO-B 1703 W/m^2	TURBO-B 71270 W/m^2
$\delta Qh/Qh$ (%)	8.49	1.64	10.47	1.60
$\delta Ab/Ab$ (%)	0.63	0.63	0.63	0.63
$\delta \Delta T/\Delta T$ (%)	3.55	1.41	26.62	12.44
$\delta q''/q''$ (%)	13.05	1.80	9.26	1.55
$\delta h/h$ (%)	13.52	2.29	28.18	12.54

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